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A Guide to Aeration/Circulation Techniques for Lake Management

Tetra Tech, Inc, Lafayette, Calif

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The application of aeration/circulation techniques to lakes are reviewed from a theoretical and practical viewpoint. The effect of destratification on algal production is related to the mixed depth with the use of a mathematical model. Procedures are given to determine air required to mix lakes of different sizes and shapes. It was found that approximately 30 scfm of air per 10^6 square feet of lake surface area can be used as a rule of thumb.

Hypolimnetic aeration systems that have been used are described in detail. Procedures for design are given.

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A GUIDE TO AERATION/CIRCULATION TECHNIQUES FOR LAKE MANAGEMENT

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FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory.

The primary mission of the Corvallis Laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lake systems; and the development of predictive models on the movement of pollutants in the biosphere.

This report provides a valuable contribution to knowledge and practice in the field of eutrophication control with lake aeration/circulation techniques.

A. F. Bartsch
Director
Corvallis Environmental Research
Laboratory

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UNITS AND CONVERSION FACTORS

The use of mixed (English-metric) units was considered to be desirable as well as unavoidable. Certain specifications and nomographs for solution of flow equations were only available in English units. Consequently, necessary computations were illustrated with English units. Because much of the information contained herein was taken from published sources it was decided to use the same units used by the originator. This minimizes errors in conversion as well as facilitates comparison to the original work. Useful conversion factors are:

1 meter = 3.281 feet
1 cubic meter = 35.32 ft^3
1 acre = 43,560 ft^2; 4046 m^2
1 acre-foot = 43,560 ft^3; 1234 m^3
^oF = 9/5 (^oC) + 32

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SECTION I

INTRODUCTION

BACKGROUND

"One of the most important problems in the pollution of inland waters is the progressive enrichment with nutrients concomitant with mass production of algae, increased water productivity, and other undesirable biotic changes" (Stumm & Stumm-Zollinger, 1972). Lakes that continue to receive nutrients progressively increase their productivity and deteriorate in water quality.

Excessive algal production which results from nutrient enrichment has direct as well as indirect implications. The algal cells can cause unsightly scums and reduce water transparency. The decomposition of settling algae can result in oxygen depletion and subsequent relase of reduced chemical species including iron, manganese and sulfides. Lack of oxygen can eliminate cold water fisheries in many lakes. High rates of algal productivity can also increase rates of nutrient cycling within a lake by providing a temporary sink to promote nutrient relase from sediments. Subsequent algal decomposition then releases some of the nutrients to the water column.

These problems associated with increasing eutrophication of lakes have received increasing attention in recent years. Lake Erie has received national recognition while thousands of smaller lakes have caused more localized concern. The Water Pollution Control Act Amendments of 1972 (PL 92-500) authorized 300 million dollars to be expended for lake restoration or pollution control measures related to eutrophication of lakes during fiscal years 1973, 1974, 1975. As a result of this growing concern and awareness of problems there has been substantial activity related to remedial and preventative measures.

"Ecological theory and a number of case histories indicate that prospects for preservation and restoration of lakes are good provided an array of remedial measures and technology is applied" (Stumm & Stumm-Zollinger, 1972). The array of preventative and remedial measures which is currently considered feasible includes both procedures to limit fertility and in-lake procedures to manage the consequences of eutrophication (Dunst, et al., 1974).

Reduce Nutrient Influx

It is generally agreed that the most desirable long-term lake management technique is to control nutrient input.

Considerable data are available to relate lake nutrient concentrations to algal production (Sakamoto, 1966; Dillon, 1974). A number of models have been developed to predict in-lake phosphorus concentrations based on loading rates, physical parameters of lake morphometry and flow rates (Vollenweider, 1969; Snodgrass and O'Melia, 1975; and Lorenzen, et al., 1976).

Reductions in nutrient influx can result from wastewater treatment, diversion, modified land use practices, treatment of inflow, or product modification.

Reduce Nutrient Availability

Several procedures to reduce the level of nutrients within lakes without changing loading rates have been devised. Dredging may be appropriate for lakes whose sediments are high in nutrients. Chemical precipitation of dissolved nutrients is possible. Dilution or flushing is possible if large quantities of low nutrient water are available. Harvesting of both algae and macrophytes can remove nutrients. Lake sediments can be sealed to prevent nutrient release.

Manage the Consequences of Nutrient Enrichment

Chemical means including the use of algicides, herbicides, and piscicides have been used to control certain undesirable conditions in enriched lakes. Physical controls such as lake deepening, harvesting, fluctuating water levels, and artificial aeration or circulation techniques can also be used to manage the consequences of nutrient enrichment.

Artificial aeration and circulation techniques can be used to improve water quality for a wide array of beneficial uses including domestic water supply, downstream releases, industrial use, fisheries management, and algal bloom control. Maintenance of aerobic conditions may also affect nutrient cycling within a lake.

SCOPE AND OBJECTIVES

Although a variety of chemical and physical control measures may be appropriate for a specific set of circumstances, it is beyond the scope of this manual to provide guidance on selection and application of techniques from this wide array of possibilities.

This manual concentrates on AERATION-CIRCULATION techniques The types of problems amenable to solution or control by these techniques and the procedures for selection of methods and expected results are described in detail. It is realized that our knowledge about lake aeration and circulation is far from complete and that there is a great deal yet to be learned. However, it is considered appropriate to provide a guidance manual which is based on a synthesis of theoretical considerations and experience. This manual therefore represents an attempt to provide the benefits of current knowledge to those who must proceed from problem identification to implementation of solutions without waiting for the results of future research.

It is not the purpose of this manual to provide another literature review but rather to synthesize from a review the important variables and relationships which affect performance of aeration/circulation systems. The manual does not cover every situation or type of lake but provides examples and procedures which can be interpreted in conjunction with site specific conditions.

LAKE MANAGEMENT

A simple example of the decision making process in lake evaluation is described below:

The first step is to determine the desired uses of the lake. These may include: domestic water supply, industrial water supply, warm or cold water fishery maintenance, non-contact water sports, swimming, and/or aesthetic enjoyment. The required water quality may vary greatly depending on the intended use.

The second step is to determine the condition and existing problems associated with the lake or impoundment. The determination of physical, chemical and biological properties of a lake may require an in-depth survey of the lake and watershed including bathymetry, oxygen profiles, nitrogen and phosphorus concentrations, algal counts, land use practices and nutrient loading rates.

The third step is to determine if existing conditions are compatible with desired uses. If water quality is suitable and there is no indication that it is deteriorating, the evaluation can be concluded. If water quality is not suitable, either desires can be modified or restoration techniques can be considered. If aeration or circulation techniques are appropriate the next step is to select and design a system.

AERATION/CIRCULATION

Benefits

The applicability of aeration/circulation techniques to improvement of water quality for domestic and industrial uses, downstream utilization and fisheries management is briefly discussed below.

Domestic Water Supply --
Aeration can greatly reduce undesirable concentrations of iron, manganese, hydrogen sulfide, carbon dioxide, ammonia and other substances associated with anaerobic conditions. These conditions contribute to offensive tastes and odors, unsightly water, discolored basins and clothing, clogging and scaling of pipes, corrosion and other undesirable conditions. These conditions can be partially alleviated by modern water treatment processes after the water leaves the lake. However, it may be less costly and better to treat the lake rather than the water after it is withdrawn. Destratification or hypolimnetic aeration can be used to treat these conditions. However, destratification will also eliminate the cold water which could be maintained with hypolimnetic aeration.

Downstream Water Releases --
Many reservoir tailwaters contain valuable cold water fisheries. These fisheries generally require water temperatures of less than 22°C (72°F) and oxygen concentrations of 5 mg/l or more. The oxygen condition can be achieved through destratification of the reservoir, but the temperature limit may then be exceeded. Alternative solutions include either aeration/oxygenation of the hypolimnion, or pure oxygen injection into the discharge only. The latter approach may be less expensive than hypolimnetic aeration, but it does not improve conditions within the reservoir. In some cases, it may not be permissible if the discharge waters are "highly" anaerobic. During anaerobic conditions, the waters may still be toxic due to carbon dioxide, hydrogen sulfide or other substances even though the oxygen concentration is apparently adequate (Irwin, Symons and Robeck, 1966). Pure oxygen injection does not result in significant stripping of unwanted gases from the water. Air injection does strip much of these gases, but it may also supersaturate the water with nitrogen gas (N_2). The water is normally 100% saturated with nitrogen initially; and nitrogen gas concentration of only 115% saturation can be toxic to fish (Rucker, 1972).

Industrial Uses --
Some industrial processes require cold noncorrosive and non-scaling water for cooling and other purposes. Hypolimnetic aeration/oxygenation can be used to maintain such water quality.

Fisheries Management --

Thermal stratification and its associated hypolimnetic oxygen depletion in eutrophic lakes is widely known to restrict fish and other biota to shallow depths (Dendy, 1945; Bardach, 1955; Ziebell, 1969). In some cases the fish may be further compressed by warm water above into a narrow band in the thermocline (Hile, 1936; Gebhart and Summerfelt, 1975) Coldwater fish such as trout and salmon are often eliminated from lakes in this manner by warm water above and anaerobic water below. At some time during the summer there may be no place in the lake with suitable living conditions for coldwater fish.

Even if thermal and chemical stratification are not lethal to the fish, they can severely stress the population. Johnson (1966) attributed low survival of silver salmon (*Oncorhynchus risutch*) in Erdman Lake, Washington to this condition. Silver salmon survival increased 500% during artificial destratification. Mayhew (1963) observed reduced growth and catch rates of several warmwater fish species in Red Haw Lake, Iowa when these fish were compressed into the upper third of the lake by stratification and stagnation.

Artificial destratification is one means of reducing or eliminating oxygen and temperature barriers to fish distributions. However, destratification is not always successful. In Lake Roberts, New Mexico, destratification eliminated thermal stratification but it also caused oxygen concentrations to approach zero throughout the entire lake and killed many fish as a consequence (McNall, 1971). In El Capitan Reservoir, California, partial destratification during 1965 greatly reduced thermal stratification but oxygen concentrations were still low in parts of the lake. Consequently, warmwater fishes did not make much use of these areas and were largely confined to areas with more than 3 mg/l oxygen (Miller and Fast, in prep.). Gebhardt and Summerfelt (1975) observed similar conditions in Lake of the Arbuckles, Oklahoma, during artificial destratification.

Destratification when properly used can eliminate both thermal and chemical barriers to fish distributions and thereby greatly expand available habitat. However, destratification may also eliminate the cold water required by coldwater fishes. When a lake is thoroughly and continuously destratified, the entire lake's temperature will approach the temperature of the surface waters before aeration began (Fast, 1968; Fast and St. Ament, 1971). If the surface temperatures were normally too warm for trout, then the entire lake may be too warm during destratification.

Hypolimnetic aeration/oxygenation if properly used will create both suitable oxygen and temperature conditions for coldwater fish. Fast (1971) first demonstrated the efficacy of this management technique in Hemlock Lake, Michigan. Before hypolimnetic aeration, the rainbow trout (*Salmo gairdneri*) were confined to a narrow band within the thermocline by warm epilimnetic waters above and anaerobic hypolimnetic waters below. During hypolimnetic aeration, the trout distributed throughout the hypolimnion and thermocline. Fast (1973a, 1973b) later created suitable yearlong trout habitat in Lake Waccabuc, New York, using a different hypolimnetic aerator (Fast, *et al.*, 1975a).

In addition to creating suitable yearlong habitat for trout, hypolimnetic aeration may allow trout stocking at a much smaller size than usual. Many California lakes for example have a winter trout fishery where "catchable" size trout are stocked during the cooler months only (Butler and Borgeson, 1965). Since these fish generally do not survive through the summer they do not sustain much growth in the receiving water. They typically are stocked at 8 to 9 inches in length. With hypolimnetic aeration and yearlong survival, it may be possible and economical to stock fingerlings or small trout and allow them to reach catchable size in the lake. The lake, rather than the fish manager, would feed the fish.

Algal Production --

Algal biomass, species composition, and rates of production can all be affected by artificial aeration/circulation techniques. Changes in available light for photosynthesis as well as pH and nutrient status may be responsible for observed changes. These factors are discussed in detail in Section II.

Application

The remainder of this guide discusses procedures to determine if aeration/circulation techniques are appropriate and design considerations related to implementation. The broad range of possibilities included with aeration/circulation techniques has been divided into two major groups: Destratification and hypolimnion aeration.

Procedures which are designed to either mix the lake or provide aeration without maintaining the normal thermal structure are included in the "destratification" category. Within this category systems may range from high energy mixing devices to low energy aeration procedures. Both mechanical pumps and compressed air can be used as mixing devices. Destratification systems can be used to control excessive algal growth under certain circumstances and can maintain aerobic conditions. However, cold water cannot be maintained when complete mixing is achieved.

Those systems which are designed to maintain the normal thermal structure of a lake while adding oxygen are included under the heading "hypolimnion aeration". Both air and oxygen have been used in such systems. Hypolimnion aeration can be an effective means to maintain aerobic conditions without losing cold hypolimnetic water which may be necessary for domestic or industrial use and is required for the maintenance of cold water fisheries.

Problem Definition and Selection of Goals --

Aeration/circulation techniques can be used to maintain desired oxygen levels and, under certain circumstances, to control algal blooms. Prior to deciding on a lake restoration technique it is necessary to identify and quantify the problem. Several surveys should be made to determine oxygen and temperature profiles as well as algal species and abundance. It is recommended that at least three surveys be conducted during summer months to quantify the extent of any problems. Samples should be collected from a sufficient number of stations and depth intervals to determine spatial variation (initially, approximately one station per 100 acres (40 hectares) at 3 foot (1 meter) depth intervals. Sampling stations should include the deepest portions of the lake. Temperature and dissolved oxygen should be measured in the field. A good quality Temperature-Dissolved Oxygen Analyzer is of sufficient accuracy for problem identification. Water samples should be taken to a competent laboratory for phytoplankton analysis. Only predominant species and total biomass as measured by chlorophyll a or ash free dry weight need be determined.

System Selection --

This manual addresses two possible management techniques: destratification and hypolimnion aeration. Each technique is appropriate for certain circumstances. Destratification can maintain aerobic conditions and control algal blooms. However, when a lake is destratified the net heat input is increased significantly and the cold water formerly contained in the hypolimnion is heated. In general, a destratified lake will have a fairly uniform temperature from top to bottom which is slightly (1-3°F) lower than the surface temperature under stratified conditions. Hypolimnion aeration can maintain cold, aerobic bottom water but does not control algal blooms.

If it is determined that excessive algal growth is not a problem but low oxygen levels are, then it must be determined if cold hypolimnion temperatures are needed. If low temperatures are required then hypolimnion aeration should be considered. However, the cause of low oxygen should first be determined to ascertain if the problem could be solved by eliminating the source.

If algal growth is a problem and cold water is not required, a high energy mixing system may be beneficial but further analysis will be required to determine the probable results. A high energy mixing system sufficient to control algal growth will normally maintain high oxygen levels.

If algal growth is a problem and cold water is required, an aeration/circulation system will not solve the entire problem. However, aerobic conditions can be maintained in the hypolimnion without disturbing the temperature profile by application of a hypolimnion aeration technique.

SECTION II

DESTRATIFICATION

BACKGROUND

Destratification or mixing of lakes has been used for two general purposes:

1. Aeration and
2. Algal Bloom Control

The need for aeration results from the fact that major oxygen consuming processes occur in the hypolimnion of lakes. Because very little oxygen is transported downward across the thermocline during periods of stratification, the available oxygen can be depleted. Such anoxic water may then require aeration for a variety of beneficial uses.

Water supply reservoirs may experience severe problems associated with anoxic conditions such as high concentrations of iron and manganese and odors associated with reduced compounds such as hydrogen sulfide. Fishery maintenance may require oxygen additions. High oxygen concentrations may be required for reservoir releases to maintain desirable biological communities downstream.

It is possible to provide the required oxygen *in situ* by artificially mixing the lake. It has been shown (Smith *et al*., 1975) that the primary mechanism of oxygen transfer is at the water surface even if compressed air is used as a mixing device. Riddick (1957) concluded that "...an aerator should be regarded as a cheap, uncomplicated and relatively efficient device for pumping water". However, in deep lakes gas transfer between the rising bubbles and surrounding water may be important.

Destratification to control algal blooms is only appropriate under certain circumstances and requires high energy systems sufficient to redistribute algal cells throughout the water column. It is believed that mixing can control algal blooms by limiting the amount of solar energy available for photosynthesis. Theoretical considerations indicate that the depth available for mixing is a controlling factor in limiting algal biomass by mixing (Lorenzen and Mitchell, 1973, 1975). It has also been suggested that pH changes induced by mixing can have a significant effect on algal species dominance. Shapiro (1973) feels "that the rate of supply of CO_2 is an important factor in regulating the qualitative nature of the phytoplankton". Blue-green algae may have a competitive advantage at high pH. It is therefore possible that lowering the pH as a result of mixing could favor non blue-green algal species over blue-green species.

Mixing may also favor non blue-green algae by eliminating the competitive advantage of blue-green algae which are often buoyant and thus able to maintain themselves at optimum light levels under quiescent conditions. The long term effects of maintaining oxic conditions on nutrient cycling have not been well established. However, the net effect should be a reduction in sediment phosphorus release.

The following sections of this chapter provide a description of past experience and methods for destratification followed by design considerations which include definition of goals, data requirements, procedures to estimate results, and selection of methods. The chapter concludes with a summary of potential problems.

EXPERIENCE AND METHODS

Dunst, et al., (1974) list 123 individual lakes where aeration and/or circulation techniques have been employed as all or part of lake rehabilitation projects. There are undoubtedly many more such projects which were not uncovered in their survey. In 1971 the American Water Works Association reported on "Artificial Destratification of Reservoirs". Of 37 water utility managers, 86% considered their projects a success. The great majority of destratification systems have used air diffusers although several have used mechanical devices.

Table II-1 summarizes some of the pertinent characteristics of selected previous destratification systems. All of these systems used compressed air as a mixing device. There is a wide range in amount of air supplied per unit volume or unit area. The ratio of air release rate to volume (Q_a/V) is shown in standard cubic feet per minute (SCFM) of air per million cubic feet of lake volume. The ratio of air release rate to surface area (Q_a/A) is shown in SCFM of air to million square feet of surface area. Those systems that provided good mixing generally used more than one standard cubic foot per minute (SCFM) of air per million cubic feet of lake volume, and more than 20 SCFM per million square feet of surface area. Lake morphometry in conjunction with weather conditions and wind exposure will also effect the required air flow to induce mixing.

TABLE II-1 CHARACTERISTICS OF SELECTED PREVIOUS DESTRATIFICATION SYSTEMS

Lake	Location		Air Release Depth ft.	Mean-Depth ft.	Volume 10^6 ft^3	Area 10^6ft^2	Power (HP)	Q_{air} SCFM	$\frac{Q_a}{V}$ x10^6	$\frac{Q_a}{A}$ x10^6	ΔT^0C Surface-Bottom	Comment	Reference
Clines Pond	Corvalis, Oregon		15	6.4	0.098	0.0153	1/4	1	10	65.3	$\sim 1^0$	good mixing	Maleug, et al., 1973
University Lake	North Carolina		30	10.5	91.5	8.714	3	14	0.15	1.61	$1-2^0$	O_2 depletion	Weiss, Breedlove, 1973
Eufaula Reservoir	Oklahoma		92.5	53	24,829	468		1200	0.05	2.56	9^0	Central pool 125 psig $1-2^0C$	Leach, Duffer, Harlin EPA 16080 10/70
Kezar Lake	New Hampshire		25	10	76.2	7.62		105	1.3	13.8	$<1^0$	15 psig - good mixing	NHWSPCC , 1971
Lake Roberts	New Mexico		30	14.3	42.7	2.986		100	2.3	33.5	$<1^0$		EPA, 1970
El Capitan	California	1970 1971	70 93	32 31	635.4 743.4	19.8 23.9	50 50	215 215	0.34 0.29	10.9 9.0	2.5^0 2.5^0	Did not mix algae	Fast, 1968
Test Lake 1	Boltz, Kentucky		62	30	125.4	4.18		112	0.89	26.8			Symons, et al., 1967
Test Lake 2	Falmouth, Kentucky		42	20	196	9.80		115	0.59	11.7			Symons, et al., 1967
Section Four Lake	Michigan		60	32	3.9	0.121	20	78	20	645	0^0	Compressor run only 8 hours a day	Fast, 1971
Ottoville Quarry	Ohio	1970 1971	55 55	29 29	2.2 2.2	0.076 0.076	3/4 2	32 78	14.5 35	422 1028	1^0 2^0	Non-continuous compressor operation	Gartman, 1973
Casitas Reservoir	California	1972 1973	140-160 140-160	85 91	8,790 10,413	103.4 114.4	150 150	630 630	0.07 0.06	6.09 5.51	4^0 1/ 7^0	Air injected about 80-100 feet off the bottom	Barnett (1971, 1975)
Buchanan Lake	Ontario, Canada		44	16.2	15	0.926	2	10	0.67	10.8	10^0		Brown, et al., 1971
Valen Lake	Ontario, Canada		15	6.5	42.4	6.52	2	10	0.24	1.53	0.5^0		MacBeth, et al., 1973
Parvin Lake	Colorado		32	14.4	30	2.08		75	2.5	36	3^0	Helixor ^{R}	Lackey (1972)
Lake Wohlford	California		45	19.2	109	5.66	50	210	1.9	37.1	$<1^0$	Compressor run 9 hours per day	Koberg & Ford (1965)
Cox Hollow	Wisconsin		29	12.5	52.3	4.18	7.5	72	1.4	17.2	$0-3^0$	Aero-Hydraulic Cannons ^{R}	Wirth & Dunst (1967)
Wahnbach Reservoir	W. Germany	1961-62 1964	140 140	63 63	1,470 1,470	23.08 23.08	15 50	71 210	0.05 0.14	3.08 9.1	$5-6^0$ 1^0		Bernhardt, 1967 Bernhardt, 1967
Hyrum Reservoir	Utah		70	35	585	19	25	100	0.17	5.3	$2-4^0$	Did not mix algae	Drury, et al., 1975
Allatoona	Georgia		140	31	16,170	522	300	1000	0.06	1.9	$4-6^0$		Raynes, 1975

1/ Temperature at surface and 120 foot depth.

Mechanical Mixing

Mechanical mixing of lakes and reservoirs has been used to a lesser extent than diffused air mixing. However, several systems have been used and may be appropriate under certain circumstances.

The Metropolitan Water Board of London routinely uses jet discharges to control stratification. Their reservoirs are supplied by pumping river water so that modifications could be made to the inlet system with little added pumping cost. In one 500 acre (22 million square feet) 70 foot deep reservoir the incoming water can be pumped into the reservoir through a series of six jets placed a few feet above the reservoir floor. The jet orifices are 36 inches in diameter and discharge water at approximately 10 feet/second. Some of the inlets are horizontal while others are inclined at angles of 22-1/2 and 45° to the horizontal. The direction of the jets relative to the peripheral embankment of the reservoir was determined by extensive trials with scale models (Ridley and Symons, 1972).

Symons (Ridley and Symons, 1972) used a 12 inch, mixed flow pump driven by a gasoline engine to destratify Vesuvius Lake in Ohio and Boltz Lake in Kentucky. These lakes were destratified by pumping water from the bottom to the surface. Boltz Lake was effectively destratified by pumping at a rate of 6.4 cubic feet per second. The lake volume was approximately 1.3 million cubic feet.

Garton and Jarel (1975) have experimented with mechanical destratification in Ham's Lake and Lake of the Arbuckles, Oklahoma. A 42 inch diameter fan blade, a 1/2 horsepower electric motor and belt driven reduction gear successfully destratified Ham's Lake in one week. Ham's Lake has a surface area of 4.4 million square feet and volume of 44 million cubic feet. Water was pumped from the surface downward.

A much larger device consisting of a 16.5 foot Curtiss-Wright propeller with a 40 horsepower Ford industrial motor pumped approximately 670 cubic feet per second down from the surface of Lake of the Arbuckles which has a surface area of approximately 103 million square feet and volume of 3185 million cubic feet at conservation storage level. The system did not completely destratify the lake but reduced the maximum temperature differential from 13°C to 4.5°C in 44 days.

Diffused Air Mixing

Release of compressed air at the bottom of lakes and impoundments has been found to be a fairly efficient mixing technique. Ease of installation and simplicity of operation add to the advantage of air as opposed to mechanical devices.

A typical installation, described by Fast (1968) is shown in Figure II-1. This system was installed at El Capitan Reservoir in California. The system uses a shore installed air compressor (LeRoi 50-S-2) which was rated at 215 cubic feet per minute, driven by a 50 horsepower electric motor.

A 1-1/2 inch nominal size galvanized steel pipe transports air from the compressor to the reservoir. From this point, a 300 foot length of 1-1/2 inch PVC plastic pipe extends along the bottom. The plastic pipe is weighted by 15 concrete block anchors. The last 100 feet of the plastic pipe are suspended almost horizontally above the bottom by 13 styrofoam floats and lengths of polyethylene anchor rope. Thirteen sets of floats with anchors are evenly spaced along the 100 feet of plastic pipe. This section is perforated by 90 holes, 1/8 inch in diameter, and sealed at its distal end. Clusters of three holes, spaced 120 degrees apart around the circumference of the pipe, are located on this section of pipe. The clusters are unevenly spaced. Beginning 100 feet from the end of the pipe, the spacing between the first six clusters is 5 feet, clusters 6 through 12 are 4 feet apart, clusters 12 through 21 are 3 feet apart and clusters 21 through 30 are 2 feet apart. This non-linear arrangement of air holes was intended to produce a uniform air release over the length of the pipe.

DESIGN CONSIDERATIONS

Aeration

For those situations when aeration is needed, algal bloom control is not necessary, and cold water is not required, a circulation device to eliminate the thermocline can be used to provide sufficient surface aeration. Although any specific lake may provide special problems, in general, if there are no unusual oxygen consuming processes it is believed that if the temperature profile can be maintained such that there are no sharp gradients and the maximum temperature difference between top and bottom is less than 2°C, sufficient mixing will have been imposed to maintain aerobic conditions. Air requirements to provide sufficient mixing are discussed under system selection.

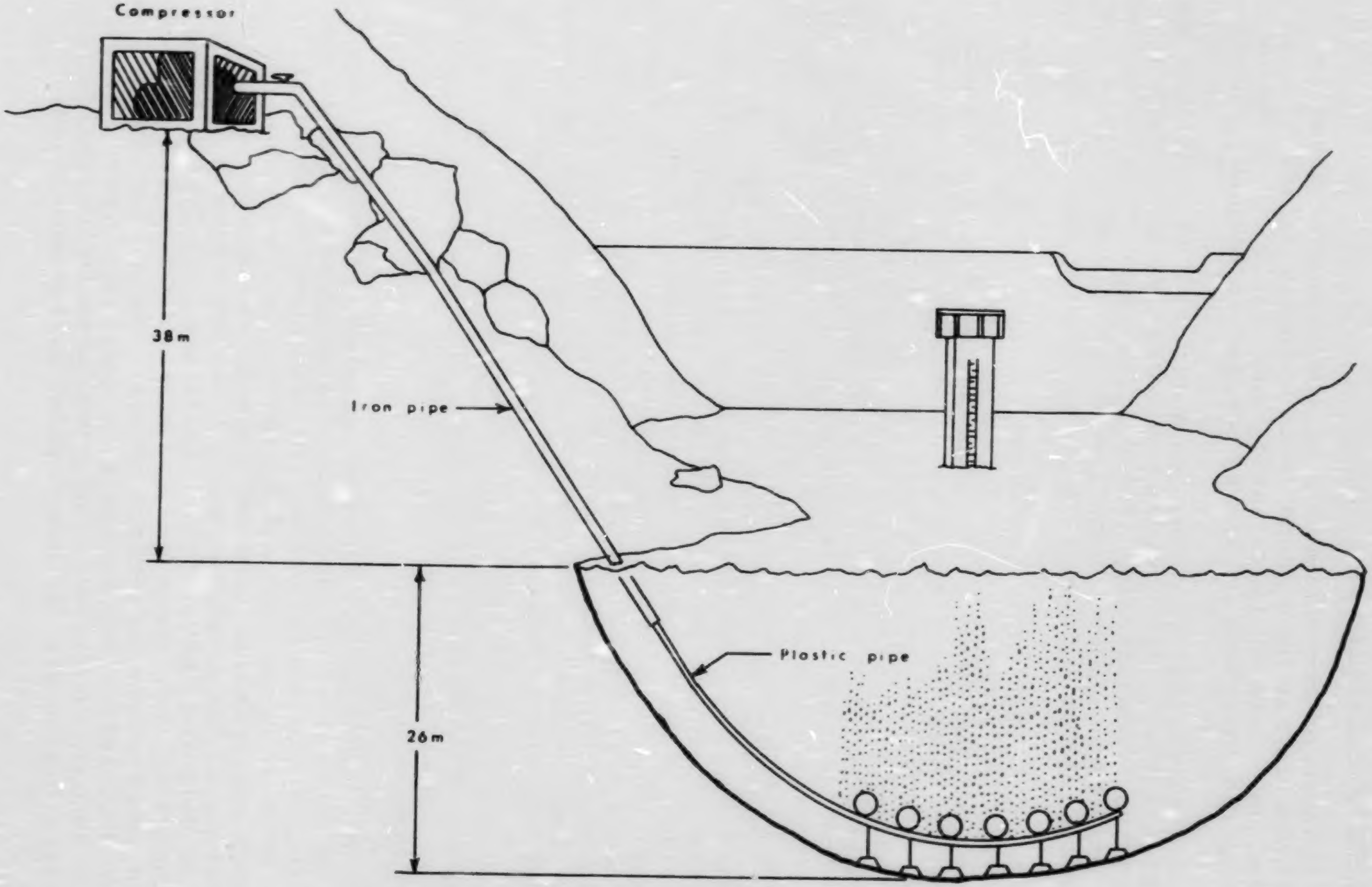

Compressor
38m
Iron pipe
Plastic pipe
26m

Figure II-1. Destratification system installed at El Capitan Reservoir, California.

Algal Bloom Control

Prior to designing a destratification system to control algal production it is important to determine the suitability of the impoundment. The procedure outlined below is taken from Lorenzen and Mitchell (1975) and is designed to provide a determination of the maximum algal biomass that could develop under both stratified and completely destratified conditions.

The evaluation procedure is based on a mathematical model of algal production and respiration. The model considered both nutrient depletion and light limitation as potential biomass limiting factors. The two mechanisms were evaluated independently and then combined to determine the upper limit to biomass production as a function of mixed depth. Nutrient limitation was considered as the capacity of the system to produce biomass prior to some essential nutrient(s) being exhausted. The total nutrient limited biomass that could be produced in a water column was shown to be

$$C \times Z = X \times Z \qquad \text{(II-1)}$$

where C = algal concentration, mg/l

Z = depth of uniform algal distribution, m

X = capacity of system to produce algal biomass before nutrient(s) is (are) depleted, mg/l

Biomass limitation by available light was determined by evaluating the balance between photosynthesis and respiration in a water column. By considering light attenuation to be a function of depth and concentration of algal cells, it was shown that at some maximum algal concentration, light would be sufficiently diminished so that total photosynthesis would equal total respiration and no further net production would take place. This maximum algal concentration, multiplied by the depth of uniform distribution (mixed depth) is the peak light limited algal biomass (grams per square meter).

It was shown that peak light limited algal biomass in the water column as a function of mixed depth could be represented by:

$$CZ = \frac{K_{max}}{R\beta}\left(\frac{1}{\Delta T}\int_0^{\Delta T} \ln\left(AI_o(t) + \{1 + [AI_o(t)]^2\}^{\frac{1}{2}}\right)dt\right) - (\alpha/\beta)Z \qquad \text{(II-2)}$$

where K_{max} = maximum specific algal growth rate, day^{-1}

R = specific rate of respiration, day^{-1}

β = incremental light attenuation coefficient caused by algal cells, $m^{-1}/mg/\ell$

ΔT = interval of integration

A = measure of alga's adaption to low light levels [1]

$I_o(t)$ = surface illumination as a function of time [1]

α = attenuation coefficient of light in the water, base e, m^{-1}

---

[1] Selection of appropriate units and devices for measuring radiation available for photosynthesis is a complex and difficult problem. Measures of illumination (foot-candle; lux) have been commonly used. However, it has been shown (Tyler, 1973) that considerable errors in estimated available energy can result from illumination measurements. The most appropriate measurement is the total quanta within wavelength limits of 350-700 nanometers in watts/cm^2 (Booth, 1976). Unfortunately, past research and easily available instrumentation do not conform to this. The following table (from Westlake, 1965) provides some conversion factors so that the best use can be made of existing work.

Active Light 390-710 nm

	Joule/m^2/sec	ergs/cm^2/sec	g cal/cm^2/min	lux
Joule/m^2-sec	1	10^3	1.43×10^{-3}	$\sim 2.5 \times 10^2$
watt/m^2	1	10^3	1.43×10^{-3}	2.5×10^2
g cal/cm^2/min (langley/min)	6.98×10^2	6.98×10^5	1	1.8×10^5
lux or meter candle	4×10^3	~ 4.0	5.70×10^{-6}	1

1 lux = 0.0929 foot candles

If CZ is plotted against Z, the light limited biomass is represented by a line having an intercept of

$$\frac{K_{max}}{R\beta\Delta T}\int_0^{\Delta T} \ln(AI_0(t) + \{1 + [AI_0(t)]^2\}^{1/2})dt \qquad (II-3)$$

and a slope of $-(\alpha/\beta)$.

Figure II-2 shows a typical plot of both nutrient limited and light limited peak algal biomass in a water column (C x Z) as functions of mixed depth, Z.

To evaluate the suitability of a lake for artificial destratification, a diagram such as Figure II-2 can be constructed. The approximate peak biomasses in the stratified and destratified cases can then be determined from the thermocline depth (stratified case) and average lake depth (destratified case). It should be noted that the analysis for the destratified case assumes that sufficient mixing takes place to maintain uniform vertical algal profiles.

To construct a diagram such as Figure II-2, the values of the individual parameters must be determined. Although various levels of sophistication can be used in these determinations, a simple evaluation should suffice for planning purposes. The following outline summarizes a procedure for evaluating the needed parameter values and constructing the diagram.

This procedure has been applied by Lorenzen and Mitchell (1975) to Kezar Lake in New Hampshire. The observed results were consistent with theoretical predictions.

1. Determine the value of X, the nutrient limited algal concentration, mg/ℓ.

    a. Bioassay: Incubation of lake samples under approximately 5000 lux for three to four weeks should give an adequate representation of maximum nutrient limited biomass. Replicate samples should be run and slight agitation provided. Biomass measurements should be made approximately every three days until no further increase is observed.

    b. Historical records: Observed peak biomass levels could be used to estimate the value of X. However, caution should be exercised to ensure that the observed levels were limited by nutrient depletion.

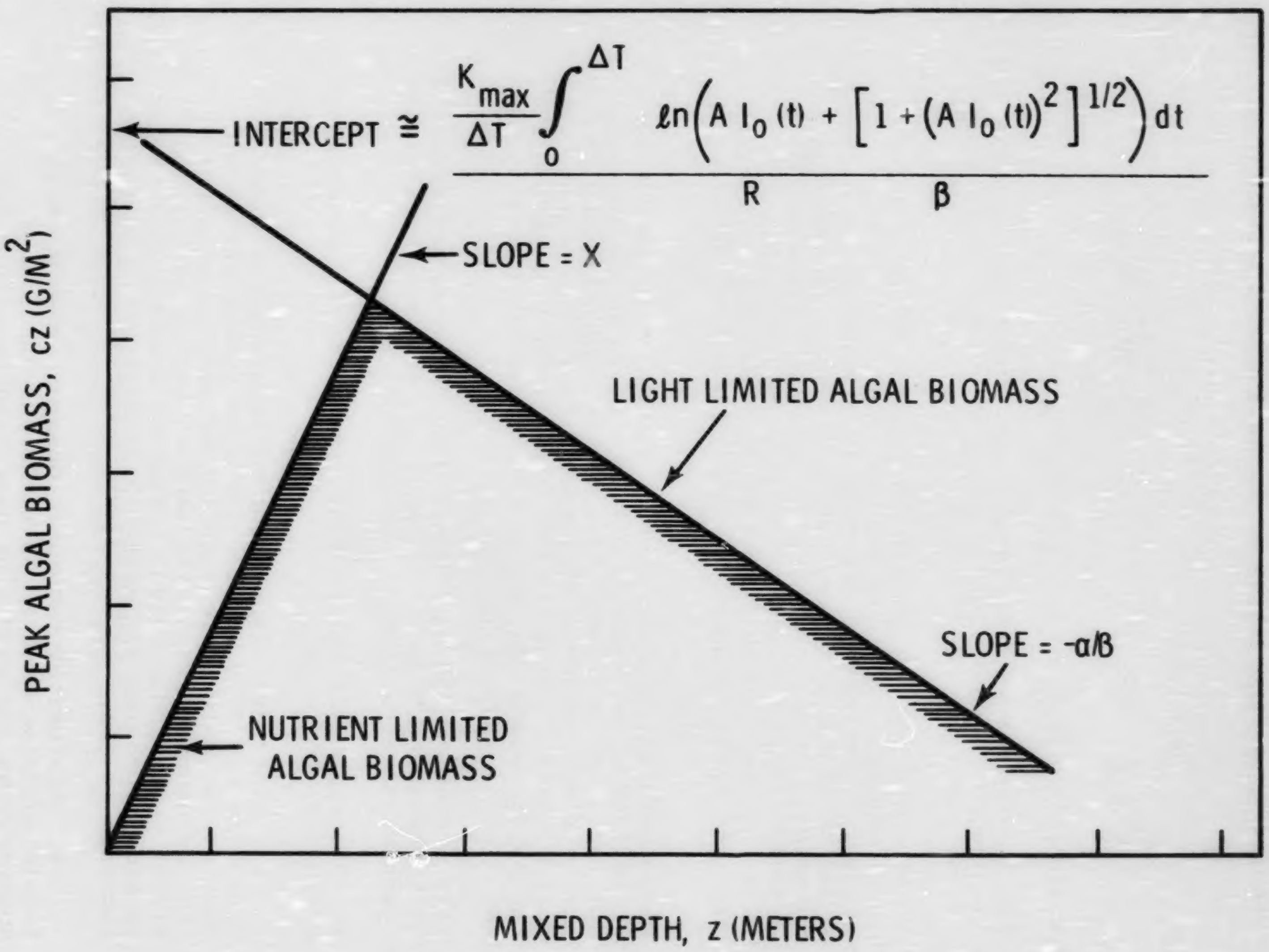


Figure II-2. Generalized plot of peak algal biomass as a function of mixed depth for both nutrient and light limitations.

2. Determine algal growth rate parameters, K_{max}, A and R.

a. Laboratory studies: Ideally, algal growth rates, as a function of light intensity in the presence of excess nutrients, should be determined in the laboratory. The maximum specific growth rate K_{max}, the rate of respiration R, and the adaption to low light A can then be determined from a plot such as Figure II-3.

b. Literature values: There are extensive data in the literature relating algal growth rates to light intensity for various algal species.

3. Determine illumination values, $I_o(t)$.

a. Field measurement: Values of illumination as a function of time can be measured directly or obtained from meteorological records.

b. Standard light day: For planning purposes a standard light day as suggested by Vollenweider (1965) may be used. For a standard 14-hr day with a maximum noon intensity of 100,000 lux and $A = 0.0005\ \text{lux}^{-1}$, the term

$$\frac{1}{\Delta T}\int_0^{\Delta T} \ln\left(AI_o(t) + [1 + AI_o(t)^2]^{1/2}\right)dt \qquad \text{(II-4)}$$

has a value of approximately 2.4.

4. Determine the incremental attenuation, coefficient, β.

a. Laboratory studies: The value of β can be determined by measuring total light attenuation coefficients with various concentrations of algal cells. A plot of total attenuation coefficient versus algal concentration, yields a line with slope equal to β.

b. Literature values: Values of β from 0.17 to 0.20 m^{-1}/ mg/ℓ dry weight have been used (Lorenzen and Mitchell, 1975; Chen and Orlob, 1975).

5. Determine the light attenuation coefficient, α.

a. Field measurement: The value of α can vary widely and should be determined for each lake. An underwater photometer can be used to measure light penetration as a function of depth. The total

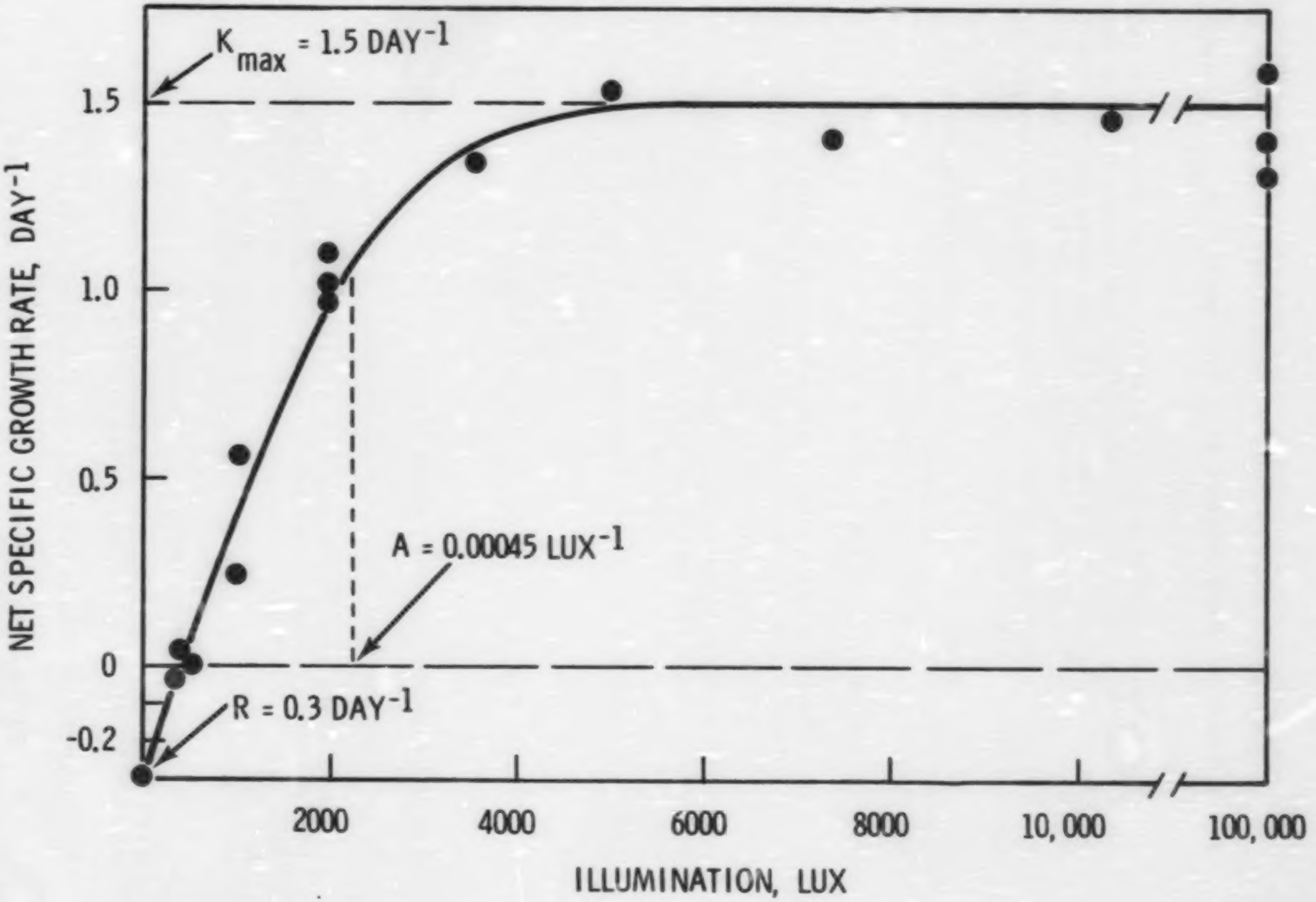


Figure II-3. Net Specific growth rates of Aphanizomenon (from Lorenzen and Mitchell, 1975)

attenuation coefficient is given by ($\alpha + \beta C$) in the expression:

$$I_d = I_o \exp[-(\alpha + \beta C)d] \qquad \text{(II-5)}$$

where: I_d = illumination at depth d, lux

I_o = surface illumination, lux

d = depth, m

α, β, and C are as previously defined.

6. Construct peak biomass diagram.

a. Nutrient limited biomass. Plot a line through the origin with slope X.

b. Light limited biomass:

(1) Evaluate intercept using the estimated parameter values.

$$\text{Intercept} = \frac{K_{max}}{\Delta TR\beta}\int_0^{\Delta T} \ln\left(AI_0(t) + [1 + (AI_0(t))^2\right)^{1/2} dt \qquad \text{(II-6)}$$

Evaluate slope = $-\alpha/\beta$

If this procedure indicates that an acceptable degree of algal bloom control can be achieved by mixing then it is appropriate to select a mixing system.

System Selection

If it is determined that artificial mixing can achieve the desired water quality then a system must be designed to impose the required circulation. There are basically two types of devices to provide induced water flow in impounded waters. Mechanical systems can pump water from bottom to top or top to bottom. Air diffusers have also been successfully used to provide vertical mixing.

Because air diffusers are by far the most commonly used mixing device, considerable effort was devoted to analysis of the relationships between air flow and water flow as well as the effects of various mixing levels on resulting temperature and algal profiles.

Induced Circulation --

There has been little research on the relationships between air release rates and water flow rates. However, the best available theory (Kobus, 1972) indicates that the amount of water flow induced by a rising bubble plume is primarily a function of air release depth and air flow rate. Kobus has shown theoretically (and to some extent experimentally) that the water flow as a function of height above an orifice is given by:

$$Q_w(x) = 35.6C(x + 0.8) \sqrt{\frac{-V_o \ln (1 - \frac{x}{h + 10.3}}{\mu_b}} \qquad \text{(II-7)}$$

where: $Q_w(x)$ = water flow m^3/sec

x = height above orifice

C = $2V_o + 0.05$

V_o = air flow m^3/sec at 1 atm.

h = depth of orifice

μ_b = $25V_o + 0.7$ m/sec

This theory was used to prepare Figure II-4 which shows the total flow of upwelled water as a function of air release rate for different depths of air release. These results illustrate that one of the advantages of a rising bubble plume is that it continues to entrain water and induce mixing all along its path.

Effects of Circulation --

The relationships established between air release and water flow were used to compute the effects of mixing on temperature and algal distributions for a range of lake sizes. The procedures used and results obtained are described in detail in Appendix A.

Table II-2 summarizes the lake characteristics and air flow required to provide mixing that results in small variations in vertical algal concentrations and temperatures. In general, the results indicate that approximately 30 SCFM of air per 10^6 square feet of surface area would be required to achieve good mixing.

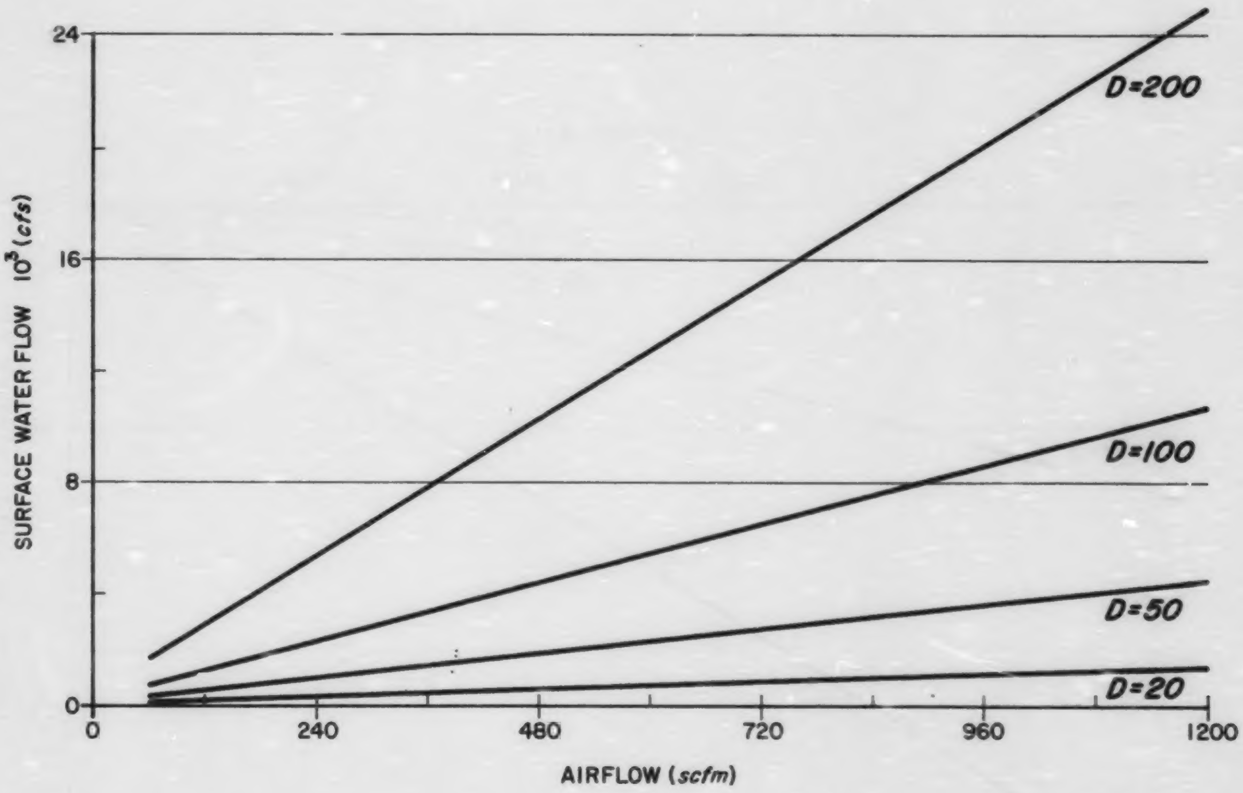


Figure II-4. Total flow of upwelled water as a function of air release rate and depth of release.

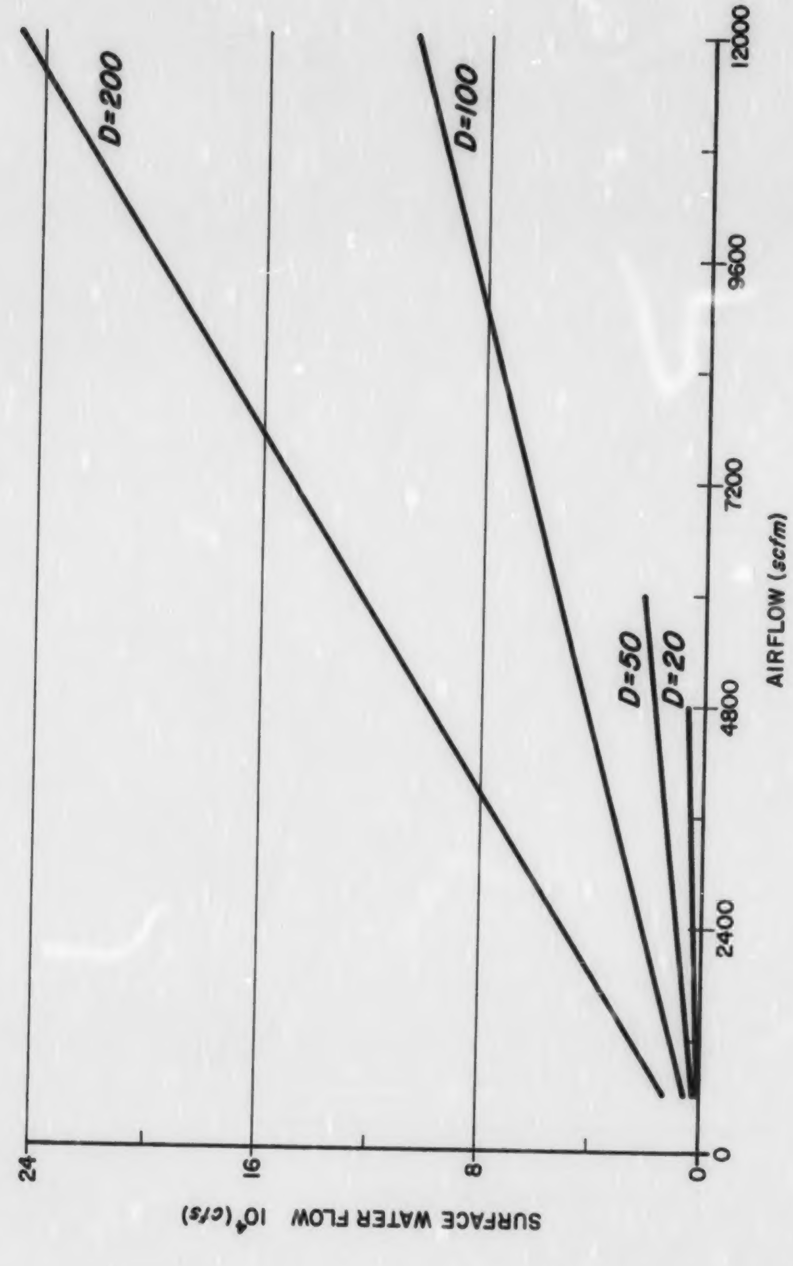


Figure II-4, continued.

TABLE II-2 APPROXIMATE AIR FLOW TO MIX VARIOUS LAKES

Lake	Avg. Depth (ft)	Max. Depth (ft)	Surface Area (ft^2)	Volume (ft^3)	Air Required (SCFM)
1	9.7	21	7.47×10^6	7.23×10^7	250
2	9.7	21	1.49×10^7	1.45×10^8	600
3	9.7	21	2.99×10^7	2.89×10^8	1200
4	9.7	21	7.47×10^7	7.22×10^8	2400
5	26	51	1.71×10^7	4.41×10^8	600
6	26	51	3.42×10^7	8.80×10^8	1200
7	26	51	8.55×10^7	2.21×10^9	2400
8	26	51	2.14×10^8	5.52×10^9	5000
9	50	100	4.26×10^7	2.10×10^9	1200
10	50	100	1.07×10^8	5.24×10^9	2400
11	50	100	2.66×10^8	1.31×10^{10}	4800
12	50	100	1.07×10^9	5.24×10^{10}	>12000
13	93	200	2.07×10^8	1.92×10^{10}	5000
14	93	200	8.28×10^8	7.66×10^{10}	10000

The results of these simulations should be used as general guidance and interpreted in view of site specific conditions compared to the cases presented here. There are an infinite number of possible conditions that could be evaluated. Many factors such as dispersion coefficients, weather conditions and lake morphometry are extremely site specific and should be evaluated on a site by site basis. The examples presented cover a range of possible lake sizes but the same weather conditions were used for all lakes and vertical dispersion coefficients were selected from the literature.

Diffuser Design

Air diffusers can be selected from numerous possibilities ranging from patented systems to simple holes drilled in polyethylene pipe. Patented systems could not be evaluated due to proprietary rights. However, the procedures to design a simple system are given so that the user can compare quotations and recommendations of various suppliers.

Once the total amount of air needed has been determined, it must be decided how it should be distributed. This decision is still very subjective and depends on local conditions.

The following general comments can be made as a result of past observations:

1) Induced mixing will normally only occur above the level of air release.

2) If the aerator is located in the deepest part of a lake, cooler water will flow toward it.

3) Because the purpose of the air release system is to promote circulation it should be located to minimize flow restrictions to a rising water column. For example, it would be preferable to locate a diffuser perpendicular rather than parallel to a dam face.

4) Air release rates have ranged from 0.02 to 2 SCFM of air per lineal foot of diffuser.

The design and layout of a diffuser system to promote vertical circulation requires the specification of a number of components including:

- Length of diffuser

- Configuration of diffuser

- Pipe size and material
- Orifice size and spacing

The length and configuration of the diffuser system is the most subjective. The primary goal is to induce circulation so the air should be dispersed as widely as possible. As a general guide, for low exit velocities, the rising plume will spread horizontally at a rate of 0.05 feet per foot rise. Orifice spacing should therefore be at least 0.1 times the depth of air release. The total length of diffuser is then determined by dividing the total air required by the flow through each orifice.

The flow through an orifice can be computed from the relation (CRANE, Technical Paper 410, 1973):

$$\omega \approx 0.525\, d^2 \; C\sqrt{\Delta P \rho} \qquad \text{(II-8)}$$

where: ω = weight flow rate, lbs/sec

d = orifice diameter, inches

C = discharge coefficient, ≈ 0.65

ΔP = pressure drop across orifice, psi

ρ = weight density, lbs/ft^3

As an example, the following flow rates were computed for air at 70°F at a range of overpressures (ΔP, pressure in diffuser - hydrostatic pressure) and operating pressures (P, pressure in diffuser) for a 1/8 inch diamter orifice.

Air Flow Rate in SCFM

P ⟶ psi

ΔP, psi	30	50	100
5	7.0	8.4	11
10	9.6	12.0	16
15	12.0	15.0	19

A uniform air flow along the length of the diffuser line can be achieved when the pressure change is small compared to pressure in the line. However, when pressure loss in the diffuser is significant the hole spacing should be decreased along the length of the diffuser. The following example illustrates the computation for a 2 inch diameter line, 500 feet long, discharging 500 SCFM of air in a 100 foot deep lake.

Inlet Pressure, P_o = 60 psi

Pressure at end of line, P (Van der Hegge Zijnen, 1951)

$$P = \left\{ P_o + \gamma \frac{V_o^2}{2g} \left[0.9 - 0.158\ R_{eo}^{-1/4}\ \frac{8}{11}\ \frac{L}{D} \right] \right\} \qquad \text{(II-9)}$$

where: V_o = inlet velocity, ft/sec

R_{eo} = Reynolds Number at inlet, $V_o\ D/\gamma$

L = line length, ft

D = line diameter, ft

γ = density of air, lb/ft^3

ν = kinematic viscosity, ft^3/sec

$$V_o = \left[(500\ \text{SCFM})\ \frac{14.7}{60} / \frac{\pi(2/12)^2}{4} \right] \frac{1}{60} = 93\ \text{ft/sec} \qquad \text{(II-10)}$$

$$\frac{V_o^2}{2g} = 136\ \text{feet}$$

$$R_{eo} = \frac{V_o D}{\nu} = 600{,}000$$

$$R_{eo}^{-1/4} = 0.036$$

$$L/D = 500/(2/12) = 3000$$

$$\gamma_{60\ \text{psi}} = 0.381\ \text{lb/ft}^3$$

$$P = (60)\ (144) + (136)(0.9-12.4)\ (.381) = 8640-596$$

$$= 8044\ \text{lb/ft}^2 = 56\ \text{psi}$$

The internal pressure at the last orifice would be approximately 56 psi. The ratio of air flow in the last orifice to the first orifice can be computed from equation II-8.

$$\frac{\text{Air flow last hole}}{\text{Air flow first hole}} = \sqrt{\frac{(8)\ (0.34)}{(12)\ (0.38)}} = \frac{1.65}{2.14} = .77$$

Uniformly spaced orifices would be adequate.

Compressor and Supply Line

Compressor selection and design of the air supply line are applicable to both hypolimnion and total aeration. The procedures to select compressor size and compute pressure losses are given in Appendix C.

Potential Problems

The most significant potential problem is inadequate performance resulting from underdesign. Anticipated results are based on achieving adequate mixing. If mixing is not adequate then goals will not be achieved.

Caution should be exercised when beginning to destratify a lake which is already stratified and low in oxygen. A rapid turnover could cause the entire lake to become anaerobic.

SECTION III

HYPOLIMNETIC AERATION

BACKGROUND

The basic purpose of all hypolimnetic aeration/oxygenation systems is to add oxygen to hypolimnetic or bottom waters without destroying the thermal stratification. Hypolimnetic aeration has been used in ice covered lakes where it is desirable to aerate the water but not to create open water conditions and in lakes which are stratified during the summer where the objective is to preserve water which is both aerated and cold. There are a variety of reasons for these objectives and a number of ways of achieving hypolimnetic aeration.

Hypolimnetic aeration was first used by Mercier and Perret (1949) to aerate the hypolimnion of Lake Bret, Switzerland without disturbing the lake's thermal stratification. Their system mechanically pumped water from the hypolimnion, discharged the water into a splash basin on shore (where it was aerated) and allowed the water to return by gravity flow back into the hypolimnion. The purpose of their system was to improve domestic water quality.

Most of the early hypolimnetic aerator development occurred in Europe. By 1974, there were 11 hypolimnetic aerator installations in Europe: Sweden (4), Germany (2), Finland (2), Switzerland (1), Norway (1), and Italy (1). Interest was subsequently awakened in the United States, and the first installation occurred in Hemlock Lake, Michigan, during 1970 (Fast, 1971). Since then at least 8 hypolimnetic aeration/oxygenation systems have been installed in the United States. These include air injection systems and systems which use liquid (or pure) oxygen.

Following Lake Bret, probably the next most significant breakthrough in hypolimnetic aeration was a system designed by Bernhardt (1967). His system was first used in 1966 to aerate the Wahnbach Reservoir's (West Germany) hypolimnion for domestic and industrial water quality control. Bernhardt has since designed two other aerators for the Wahnbach Reservoir. His most recent design is one of the most efficient in terms of energy required per mass of oxygen dissolved and in terms of operating expense.

Beginning in 1969, Bengtsson, et al., (1972) in Sweden and Fast (1971) in the United States designed and tested several hypolimnetic aerators. These all use air injection with either a full air lift to the lake's surface, or a partial air lift within the hypolimnion. More recently a hypolimnetic oxygenator was tested in Ottoville Quarry, Ohio, and Attica Reservoir, New York (Matsch, 1973: Fast, et al., 1975b). This system uses liquid (or nearly pure) oxygen and a mechanical water pump.

Experience and Methods

A synoptic survey of described and proposed hypolimnetic aeration/oxygenation systems is presented in Appendix B. These systems can be categorized as mechanical agitation systems, pure oxygen injection systems, and air injection systems. The air injection systems can be further subdivided into full air life designs, which lift the water to the surface and then return it to the hypolimnion, partial air lift designs which aerate the water and discharge to the hypolimnion without transport to the surface, and downflow air injection systems which use mechanical pumping and inject air to the water returning to the hypolimnion. Thirteen of the nineteen described systems have apparently been field tested, although details of the tests are not available for all systems.

A review of these systems indicates that two basic air lift designs appear to have general application. These designs are in essence modified versions of earlier designs by Fast (1971) and Bernhardt (1974). Suggested improvements involve construction and materials modifications that should reduce capital costs, improve the appearance of the aerators, and simplify assembly and installation.

The full air lift hypolimnetic aerator design by Bernhardt (1974) has the highest reported efficiency (Table III-1). Bernhardt reported a 50% oxygen absorption rate and an energy efficiency of 2.4 lbs O_2/kw-hr. His original design (Figure III-1) is rather bulky and may be difficult to install. Suggested modifications include (Figure III-2): (1) use of corrugated pipe and flexible sheeting construction. Both the upwelling and downwelling tubes may be constructed of plastic or rubber sheeting, such as commonly used for pond lining. This material is highly flexible, durable and comes reinforced with nylon. Its life expectancy in water is about 20 years. If the upwelling arm is constructed of this sheeting, it must be fit over a rigid framework, otherwise it will collapse during air injection and water flow. The downwelling pipe should not need rigid reinforcement since the pressure of the outflowing water should maintain its form; (2) use of half-round corrugated pipe for the

TABLE III-1 OBSERVED AND CALCULATED OXYGEN ABSORPTION AND ENERGY EFFICIENCY FOR SEVERAL HYPOLIMNETIC AERATION/OXYGENATION SYSTEMS

Hypolimnetic Aerator Installation	Estimated lbs. oxygen dissolved per kw-hr.	Percent Oxygen Absorption	Influent (to Aerator) oxygen concentration	Source of observation or data for calculations
A. Full Air Lift				
Wahnbach I	2.1	50	<4	Bernhardt (1967)
Wahnbach II	2.4	50	<4	Bernhardt (1974)
Mirror Lake	0.7	9-14	0.0	Smith, *et al.*, (1975)
Larson Lake	0.7	14-23	<7.5	Smith, *et al.*, (1975)
Tullingesjön	0.5	8.1	0.1	Bengtsson, *et al.*, (1972)
Järlasjön	0.7	10.3	0.0	Bengtsson, *et al.*, (1972)
	0.4	5.3	5.0	Bengtsson, *et al.*, (1972)
B. Partial Air Lift				
Lake Waccabuc	1.2	10.6	4	Fast (1973a,b)
C. Oxygen Injection				
Ottoville Quarry	0.5	>95	>8	Matsch (1973)
Attica Reservoir	0.4	>95	<5	Matsch (1973)
Spruce Run 1973	0.8-1.0	30-41	<0.5	Whipple, *et al.*, (1975)
1974	0.4-0.8	18-30	<4	Whipple, *et al.*, (1975)

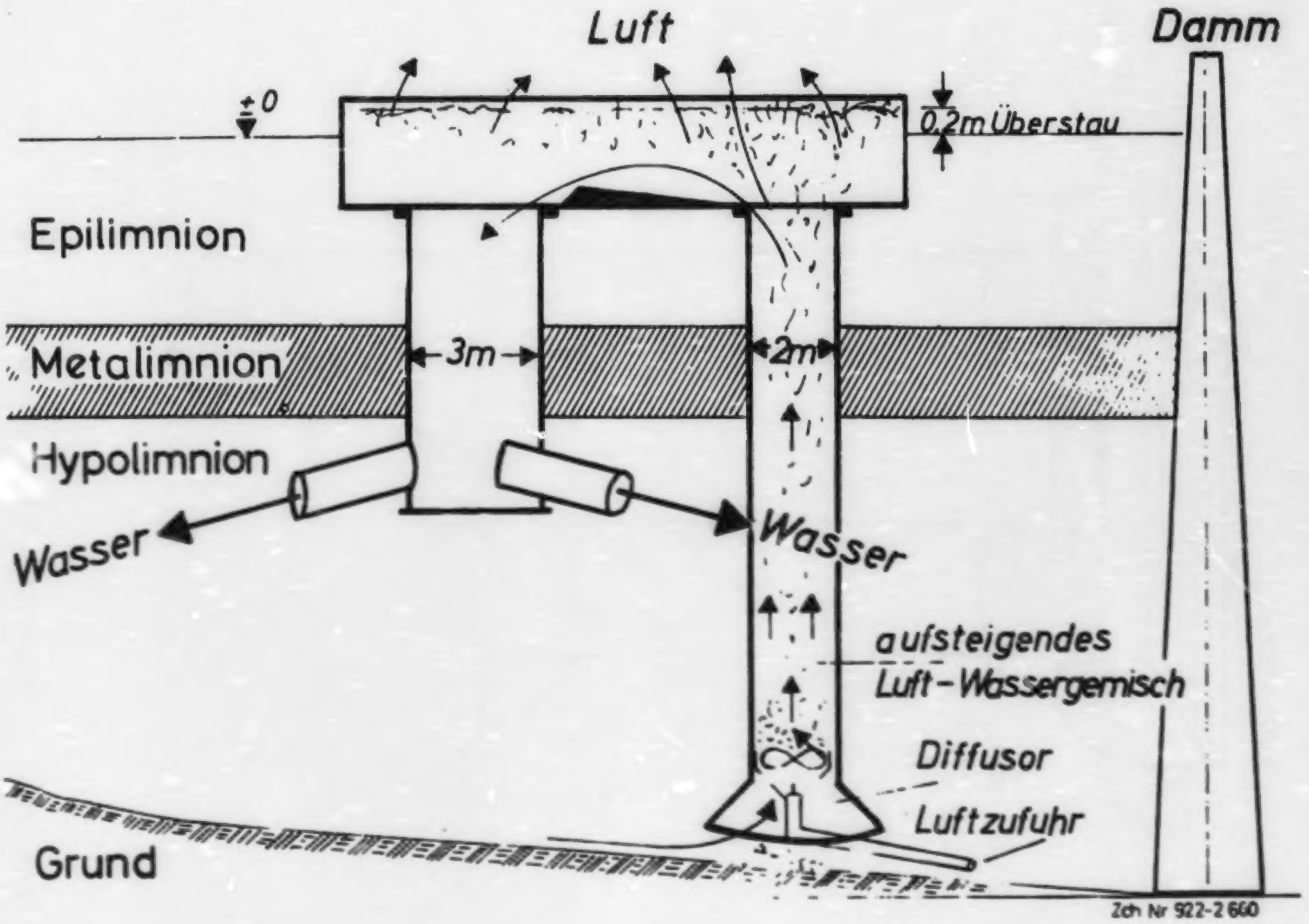

Luft
Damm
±0
0,2m Überstau
Epilimnion
Metalimnion
3m
2m
Hypolimnion
Wasser
Wasser
aufsteigendes
Luft-Wassergemisch
Diffusor
Luftzufuhr
Grund
Zch Nr 922-2 660

Figure III-1. Hypolimnion aerator used by Bernhardt (1974) in the Wahnbach Reservoir.

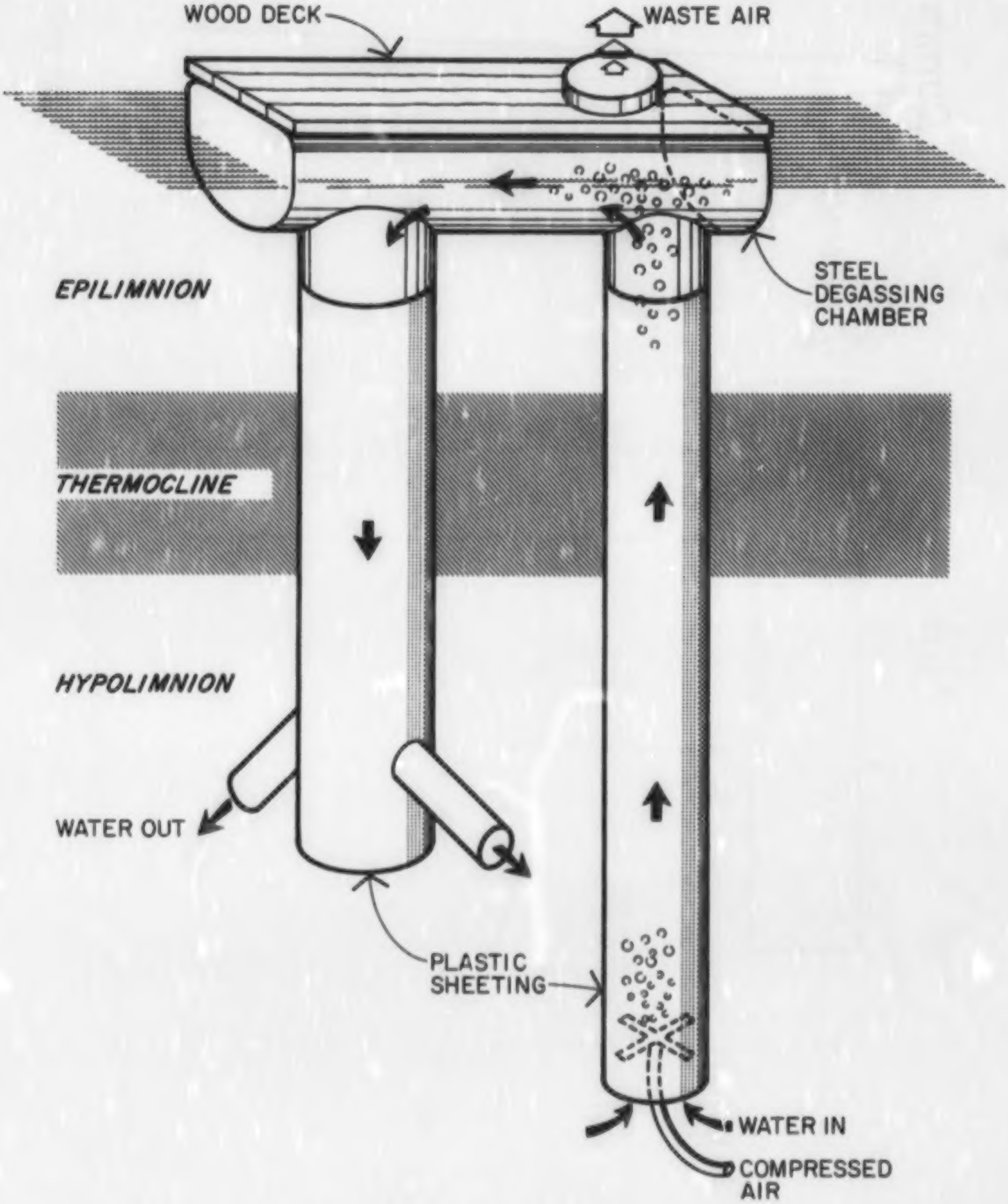

WOOD DECK
WASTE AIR
EPILIMNION
STEEL DEGASSING CHAMBER
THERMOCLINE
HYPOLIMNION
WATER OUT
PLASTIC SHEETING
WATER IN
COMPRESSED AIR

Figure III-2. Suggested modifications to Bernhardt hypolimnion aerator.

degassing chamber. This will reduce weight, costs and make the chamber more aesthetically appealing. If a 9 foot diameter degassing chamber is used and the water level is at midpoint, then the chamber will emerge from the water 4-1/2 feet if full round pipe is used but less than one foot if half-round pipe is used; (3) the half round degassing chamber can be covered with wooden planking to further improve its appearance, utility, and safety. It can be used for a recreation float; and (4) flotation of the aerator can be easily provided by extensions of the degassing chamber (Figure III-3). The end chambers may be filled with polyurethane foam. In addition, it is advisable to install ballast tanks inside these end-chambers so that the aerator can be adjusted vertically or leveled when in operation. Leveling can be accomplished by pumping water into or out of the respective ballast tanks.

The hypolimnetic aerator described by Fast (1971) is also a full air lift design (Figure III-4). Although its original efficiency was not as great as Bernhardt's, a modified version (presented here) should be as efficient, simpler and cheaper to construct, and easier to install. Proposed modifications include the use of plastic materials for the upwelling and downwelling pipes. The upwelling pipe will need reinforcement.

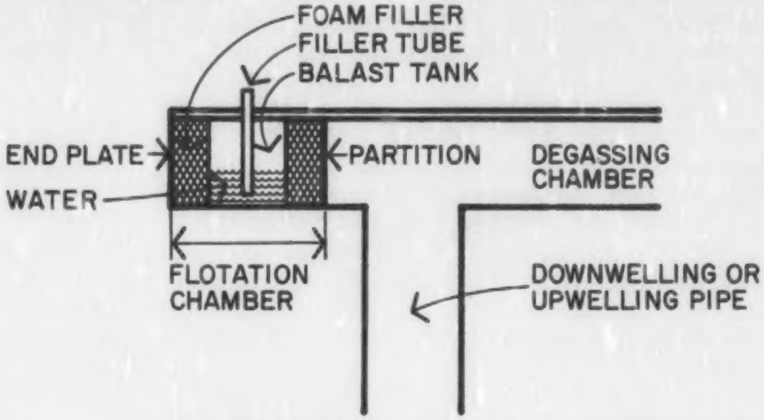
DESIGN CONSIDERATIONS

Certain data are required for sizing any hypolimnetic aerator to a given lake. The data needed will depend on the specific lake, but should include at least monthly oxygen and temperature profiles during one or two seasons, and a determination of water volume as a function of depth.

Hypolimnetic Volume Estimates

Water volumes within any depth interval are generally calculated from a bathymetric map as discussed by Welch (1948). Volume estimates for each five foot (or less) depth interval are desirable. The volumes of respective depth intervals will be used to calculate oxygen depletion rates. The total volume of the hypolimnion is also required and can be estimated from the volume-depth relationships and temperature profile data.

The hypolimnetic volume can be estimated by reviewing a set of temperature profiles during summer stratification. These profiles must be interpreted in order to account for thermocline erosion during aeration. For example, before aeration began in Ottoville Quarry, the hypolimnion extended from about 8 m to the bottom (Figure III-5), and contained


FOAM FILLER
FILLER TUBE
BALAST TANK
END PLATE
PARTITION
DEGASSING CHAMBER
WATER
FLOTATION CHAMBER
DOWNWELLING OR UPWELLING PIPE

X-SECTION THROUGH FLOTATION TANK

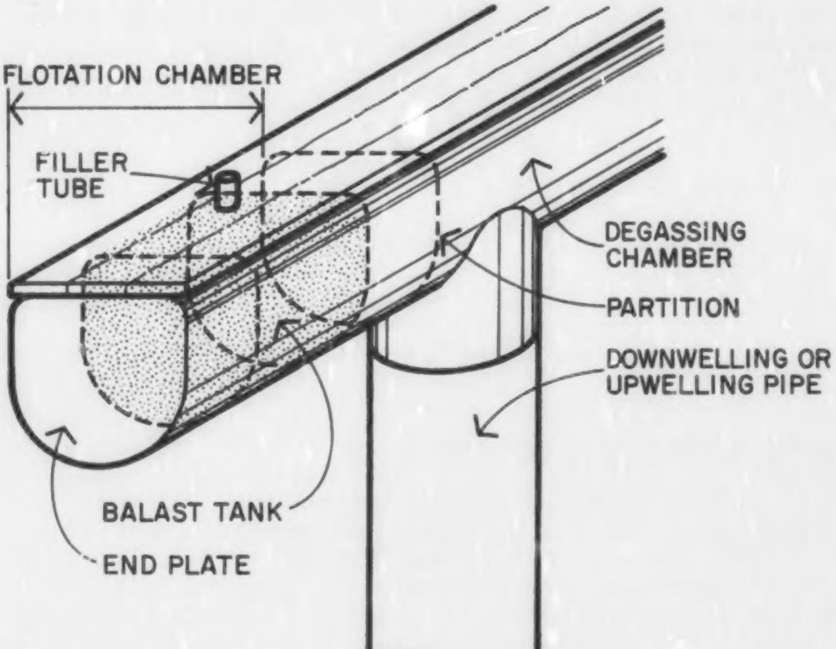

FLOTATION CHAMBER
FILLER TUBE
DEGASSING CHAMBER
PARTITION
DOWNWELLING OR UPWELLING PIPE
BALAST TANK
END PLATE

Figure III-3. Hypolimnion aerator degassing chamber details.

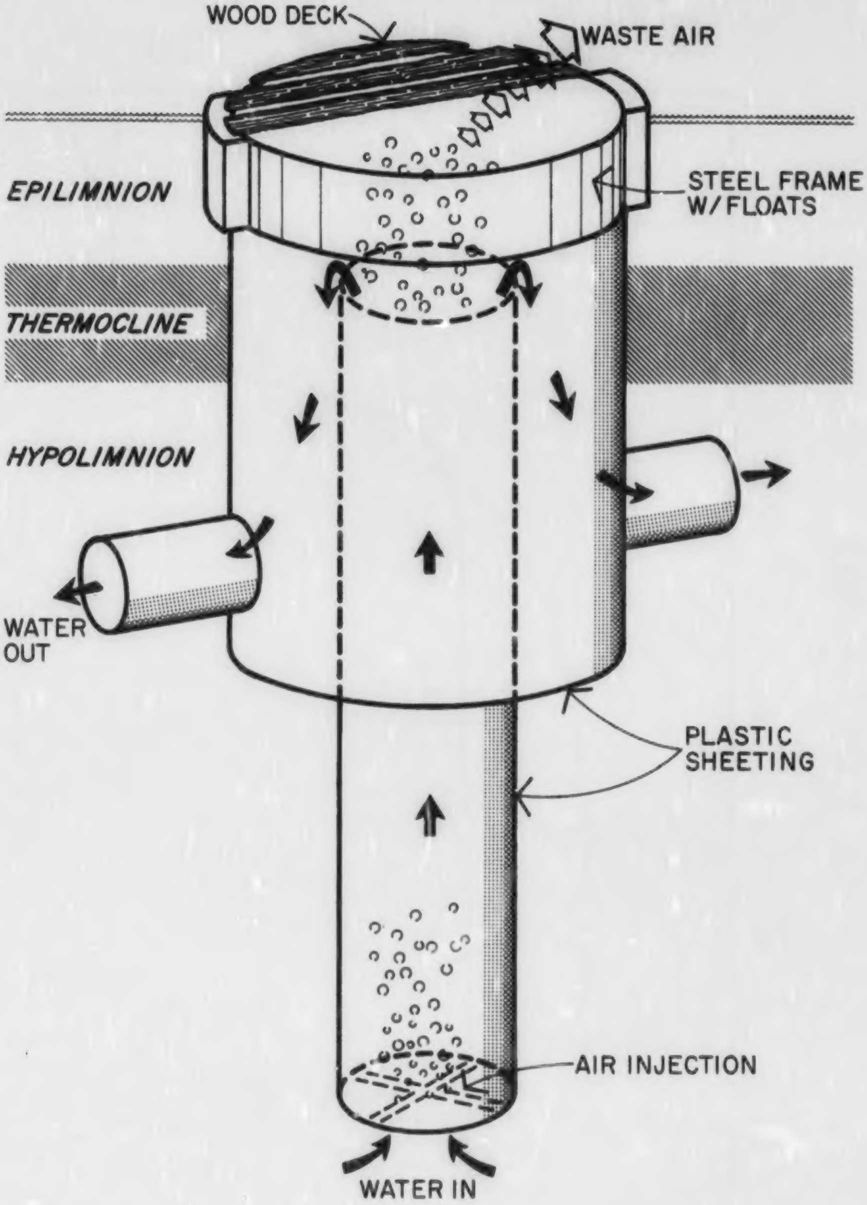

WOOD DECK
WASTE AIR
EPILIMNION
STEEL FRAME W/ FLOATS
THERMOCLINE
HYPOLIMNION
WATER OUT
PLASTIC SHEETING
AIR INJECTION
WATER IN

Figure III-4. Hypolimnion aerator by Fast (1971).

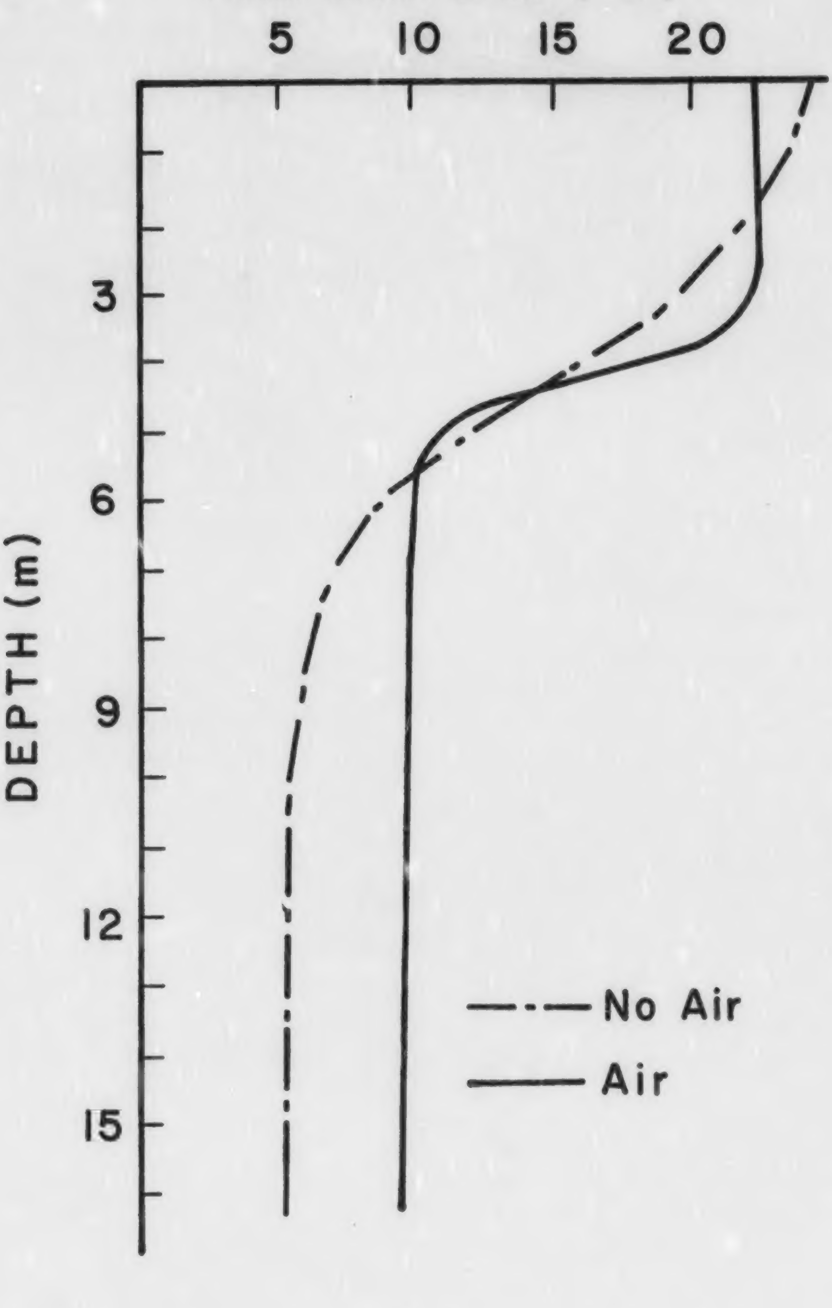


Figure III-5. Temperature profiles in Ottoville Quarry with and without hypolimnetic aeration.

24.1×10^3 m^3 of water. This profile would be relatively stable during a summer without artificial aeration. However, when the quarry's hypolimnion was artificially oxygenated, the thermocline was "sharpened" and pushed to a shallower depth. During two summers of hypolimnetic aeration the hypolimnion extended from 5 m to maximum depth and contained 35.2×10^3 m^3. Increases in hypolimnetic volume during aeration have been observed elsewhere (Fast, 1975). Since most reservoir basins are funnel shaped, a difference of only a few meters in hypolimnetic depth can represent a very large increase in the volume of water which must be circulated and aerated during hypolimnetic aeration. In many cases, the hypolimnetic volume during aeration may exceed the non-aerated hypolimnetic volume by 50% or more. If this situation is not considered, then the aeration system may be undersized and inadequate.

Oxygen Consumption Rates

The rate of oxygen consumption in water (g O_2/m^3/day) and by the sediment (g O_2/m^2/day) can be used to estimate oxygen input requirements during aeration (g O_2/day). The oxygen consumption rates can be calculated from estimates of sediment and water respiration using techniques described by Edberg and Hofsten (1973) or Edwards and Rolley (1965). These methods involve incubating a sediment core sample in the lab or in a respiration chamber placed over the sediment, and incubating water samples from different depths. The rate of oxygen depletion or consumption is observed, and the respective values are multiplied by the profundal sediment area and hypolimnetic water volume. The sum of these products represents an estimate of the total oxygen consumption rate of the hypolimnion. This technique has the advantage that it can be used any time of the year, even after the hypolimnion has become anaerobic or during periods when the lake is well mixed such as at overturn. However, experience indicates that this method tends to underestimate the hypolimnetic oxygen consumption rate during aeration.

The most accurate estimates of hypolimnetic oxygen consumption are derived from observing the rate of oxygen depletion following the onset of thermal stratification. The hypolimnetic oxygen depletion rate following thermal stratification in the spring-summer is probably preferable, but the fall-winter stagnation may also be used in those lakes with ice cover. These methods are limited to one or two periods of the year. These periods can be very short in those lakes with high depletion rates. For example, if the depletion rate is 1 mg O_2/ℓ/day and the water is saturated with oxygen when thermal stratification develops, then the oxygen will be essentially absent within two weeks. If the lake is monomictic (i.e. one overturn per year) there will be only one brief opportunity to observe the oxygen depletion rates.

The rate of oxygen depletion is calculated by first determining the initial oxygen concentration.

$$\text{Total Hypolimnetic Oxygen Content} = \sum_{i=1}^{n} V_i\, C_i \qquad \text{(III-1)}$$

where: V_i = water volume in the ith depth interval (m^3)

C_i = oxygen concentration in the ith depth interval (grams O_2/m^3)

n = number of depth intervals within hypolimnion

The total hypolimnetic oxygen content is then plotted against time as shown in Figure III-6. This plot yields a curve from which the rate of oxygen depletion can be calculated. The depletion rate in kg/day is calculated from the slope of a regression line through selected data points. Generally, the points which give a maximum depletion rate are chosen. The rate of depletion is concentration dependent and decreases as the hypolimnetic oxygen content approaches zero.

This method underestimated by 30% the oxygen consumption rate during hypolimnetic aeration of Lake Waccabuc. The oxygen depletion rate was about 2.1 mg/ℓ/week during the spring prior to aeration, but the lake consumed 3.0 mg/ℓ/week during steady state aerated conditions and hypolimnetic oxygen concentrations of 4.0 mg/ℓ. Overholtz (1975) found closer agreement between oxygen depletion rates in Ottoville Quarry and oxygen consumption during aeration. Depletion rates averaged 1.3 mg/ℓ/week, while consumption rates were 1.0 mg/ℓ/week. However, Smith, et al., (1975) found that the consumption rate in Larson Lake, ". . . during aeration was as much as three to four times as great as the normal depletion rate." Factors which could account for greater oxygen consumption during aeration include: (a) increased water circulation caused by the aerator, and thus more renewal of the mud-water interface; (b) increased

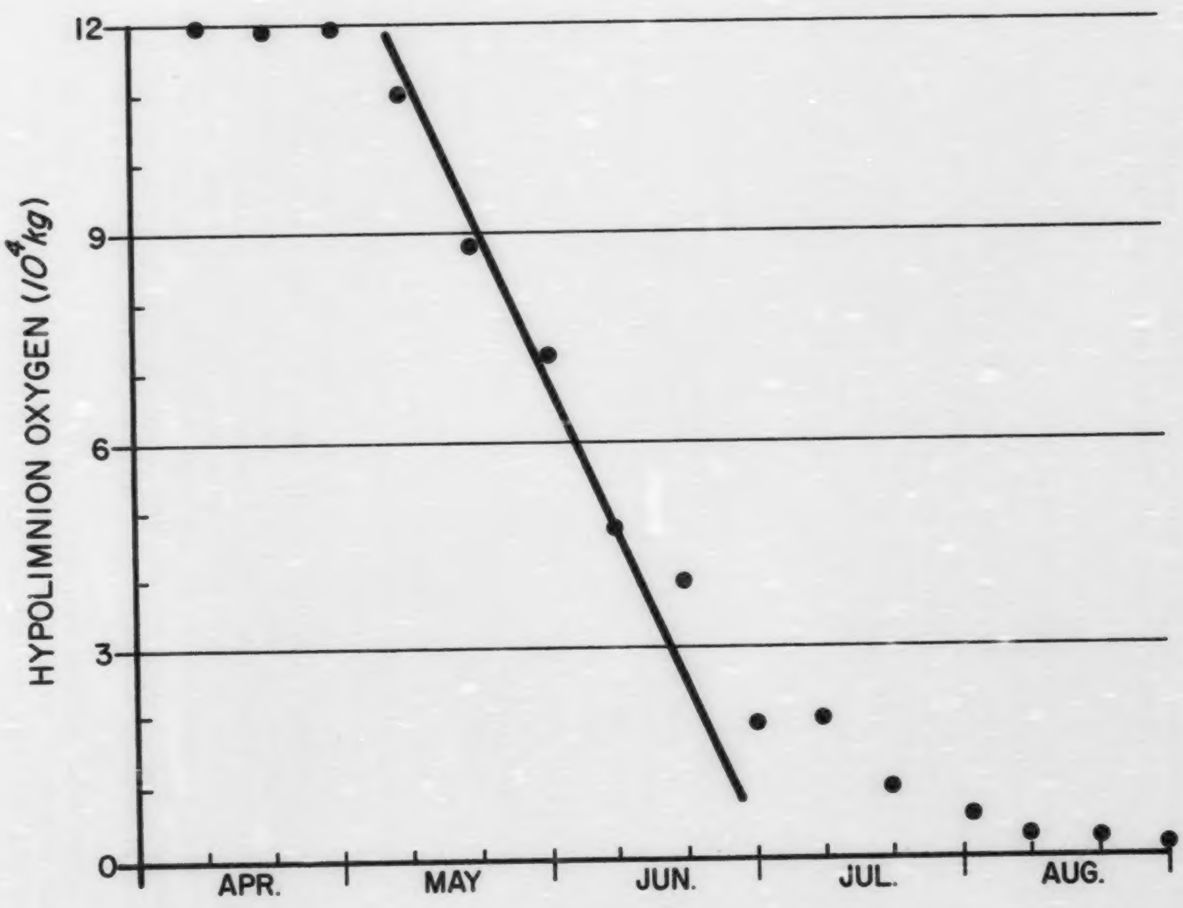


Figure III-6. Example of oxygen depletion rates data.

circulation of water through the sediments by burrowing organisms under well aerated conditions. Midge larvae, oligochaetes and other benthic organisms can circulate substantial quantities of water. Brinkhurst (1972) reports values of 600 ml of water/m^2/hour; (c) vertical mixing of sediments, caused by benthic organisms and; (d) increased respiration and decomposition due to temperature increases. Hypolimnetic aeration has caused temperature increases ranging from a few degrees to more than 9°C.

Hypolimnetic oxygen depletion rates without aeration can vary considerably from year to year within a given lake. For example, depletion rates at Lafayette Reservoir ranged from 0.35 to 0.82 mg O_2/ℓ/week (Table III-2). Values for nearby San Pablo Reservoir were much more uniform. Smith, et al., (1975) observed substantial variation in oxygen depletion rates without aeration in both Mirror and Larson Lakes. This variation was greatest in Larson Lake where depletions (without aeration) ranged from 0.08 to 2.31 mg O_2/ℓ/week.

Unfortunately if the oxygen depletion is measured for only one season then the amount of yearly variability is unknown. In these cases, ample allowance should be made for both yearly variation and for possibly increased consumption during aeration.

Oxygen Input Capacity

The oxygen input capacity will depend on: (a) desired oxygen concentration, and (b) expected oxygen consumption rate during aeration. In some cases, hypolimnetic aeration may be successful even though it does not increase the hypolimnetic oxygen concentration above zero. Lake Brunnsviken in central Stockholm, Sweden is a case in point. During winter and summer stagnation large amounts of hydrogen sulfide accumulated in the deep waters. This gas was vented to the atmosphere at spring and fall overturns to the chagrin of the surrounding inhabitants and businesses. Hypolimnetic aeration of Brunnsviken has prevented the accumulation of hydrogen sulfide in the lake even though the hypolimnion still has no oxygen. A larger system would be required in order to maintain oxygen above zero.

If iron and manganese are a problem, then oxygen concentrations above 2 mg/ℓ should prevent these substances from coming into or remaining in solution (Bernhardt, 1974).

TABLE III-2 HYPOLIMNETIC OXYGEN DEPLETION RATES FROM SELECTED EUTROPHIC LAKES AND RESERVOIRS

Lake or Reservoir	Year	Time of Year	Oxygen Depletion ($\text{mgO}_2/\ell/\text{wk}$)	Source of observation or data for calculations
El Capitan, CA.	1967	S	0.43	Fast (1968)
San Vicente, CA.	1973	S	0.25	Unpublished data (Fast)
Lafayette, CA.	1960	S	0.82	Unpublished data (Fast)
	1961	S	0.62	Unpublished data (Fast)
	1962	S	0.62	Unpublished data (Fast)
	1963	S	0.75	Unpublished data (Fast)
	1964	S	0.35	Unpublished data (Fast)
	1965	S	0.67	Unpublished data (Fast)
	1966	S	0.77	Unpublished data (Fast)
San Pablo, CA.	1969	S	0.42	Unpublished data (Fast)
	1970	S	0.40	Unpublished data (Fast)
	1971	S	0.38	Unpublished data (Fast)
	1972	S	0.38	Unpublished data (Fast)
	1973	S	0.44	Unpublished data (Fast)
Waccabuc, NY.	1973	S	2.1	Fast,(1973a,b)
	1973	S-A	3.0	Fast,(1973a,b)
Ottoville, OH.	1973	S	1.32	Overholtz (1975)
	1973	S-A	1.00	Overholtz (1975)
	1973	(1)	1.26	Overholtz (1975)
Mirror, WI.	1971-72	W	0.28	Smith, *et al.* (1975)
	1972	S-A	>7.0	Smith, *et al.* (1975)
	1972-73	W-A	>2.5	Smith, *et al.* (1975)
	1973	S	1.3	Smith, *et al.* (1975)
	1973	S-A (2)	2.6	Smith, *et al.* (1975)
Larson, WI	1971-72	W	0.59	Smith, *et al.* (1975)
	1972	W	0.26	Smith, *et al.* (1975)
	1972	F	1.75	Smith, *et al.* (1975)
	1972-73	W	0.08	Smith, *et al.* (1975)
	1973	W	1.54	Smith, *et al.* (1975)
	1973	W-A	0.35	Smith, *et al.* (1975)
	1973	W	0.77	Smith, *et al.* (1975)
	1973	S	2.31	Smith, *et al.* (1975)
	1973	S-A	7.0	Smith, *et al.* (1975)
	1973	F	1.82	Smith, *et al.* (1975)

S = Spring or Summer rates
F = Fall rates
W = Winter rates (under ice cover)
A = During artificial aeration (hypolimnetic)
(1) hypolimnion circulated but no oxygen added
(2) July 12 to July 21

Oxygen concentrations of less than 3 mg/ℓ will be unsatisfactory for most fish in most instances, but oxygen below this level may be suitable for fish forage organisms such as benthic fauna and zooplankton (Fast, 1971, 1973b). Fish vary greatly in their need for oxygen depending on such factors as temperature, species, activity level, maturity and physiological state. Most fish can live long periods at 2 mg O_2/ℓ and low temperatures, while some can survive at 1 mg O_2/ℓ or less, providing that toxic concentrations of hydrogen sulfide, carbon dioxide, ammonia or some other substance are not present (Doudoroff, 1957). Fast (1973a) and Overholtz (1975) successfully stocked rainbow trout into the hypolimnions of lakes which were being aerated artificially even though the oxygen concentrations were only 4 mg/ℓ. The trout utilized the aerated hypolimnion which were each at 10°C. However, Miller and Fast (in prep.) found that warmwater species did not utilize the deep waters with less than 3 mg O_2/ℓ at El Capitan Reservoir while the reservoir was being destratified even though the reservoir was nearly isothermal. Although fish can and do utilize low D.O. water, fishery biologists generally accept limits of 5 mg O_2/ℓ for coldwater fish (Doudoroff and Shumway, 1967). These limits are generally accepted even though it has been shown that any value below air saturation (at the surface) can restrict activity, growth and reproduction (Doudoroff and Shumway, 1967; Shumway and Palensky, 1975).

In practice, it is highly desirable to oversize the aeration system to allow for unforeseen variations in oxygen consumption rates, hypolimnetic volume increases, temporary equipment shutdown, or other factors. For example, if the observed rate of oxygen depletion is 3.5 mg/ℓ/week and the hypolimnetic volume is 2000 acre-feet, then the oxygen depletion rate is 1.9 lbs/min. It would be desirable to size an aeration system to inject between 2.5 and 3.0 lbs O_2/min. at the desired maintenance oxygen concentration. The maintenance level is important since the efficiency of most aerators is dependent on the ambient oxygen concentration. The added costs to oversize a system are generally a small portion of the total capital costs. If the system is over capacity then it does not need to operate continuously. Intermittant operation of an oversized system can result in satisfactory oxygen levels and operating costs comparable to the continuous operation of a smaller system.

Aeration Devices

The following discussion describes procedures to select and to size components of the aerator system. The discussion is limited to those systems suggested earlier.

Air Required --

The required air supply is based in part on the computed oxygen consumption rates. However, because air is used as a pump to circulate the water, the air required to provide circulation must also be considered.

Oxygen absorption efficiencies for compressed air have been reported to vary from 5 to 50% (Table III-1). This efficiency is a function of many factors including: depth of air injection, bubble size, oil content of air, chemical characteristics of the water, air to water ratios in the upwelling pipe, and most importantly, oxygen deficit in the water being aerated. The precise relationships between these factors are not well understood. However, a simplified approach to design can provide useful guidance.

It has generally been observed that upwelled water is saturated with oxygen by the time it reaches the surface of full air lift devices. If it is assumed that water reaching the surface is saturated, then the amount of flow required to maintain a specified oxygen level can be computed. The air required to provide that flow can also be calculated as a function of aerator geometry. The following example is used to illustrate the procedure.

Given: 1) Design oxygen depletion rate = 0.1 mg/ℓ/day

2) Hypolimnetic volume = 10^7 m^3

3) Maximum depth = 110 feet

4) Required D.O. = 5 mg/ℓ

5) Hypolimnic Temperature = 55°F

Solution: 1) The minimum oxygen requirement is

$0.1\ \text{mg/}\ell\text{/day} \times 10^7 \text{m}^3 = 1 \times 10^9\ \text{mg/day}$

$= 1 \times 10^6\ \text{g/day}$

air @ 21% O_2 = 8.5 g O_2/ft^3

therefore need $\frac{1,000,000}{8.5}$ = 118,000 ft^3/day

= 82 cfm

2) Required water flow if oxygen concentration increased from 5 mg/ℓ to 9.5 mg/ℓ.

$$\frac{1 \times 10^6 \text{ g } O_2 \text{ needed}}{4.5 \times 10^{-3} \text{ g/}\ell} = 222 \times 10^6 \ \ell\text{/day}$$

$$= 7.778 \times 10^6 \text{ ft}^3\text{/day}$$

= 5401 cfm

3) Air flow to give 5500 cfm of water in 100 foot upwelling pipe (see Appendix D, Figure D-1).

Q_a (SCFM)	Diameter (ft)
451	4
150	5
70	6
36	7
21	8

An air flow rate of 150 standard cubic feet per minute (SCFM) and a 5 foot diameter upwelling pipe would be selected. This computation assumes that half of the potential energy is needed for upflow and half for downflow. Therefore, the downwelling pipe(s) should have the same or less total head loss as the upwelling pipe.

Air Source --
The usual air source is an air compressor located on the shore or a raft. There are a wide variety of compressor designs and manufacturers. The most appropriate compressor for a given aeration system will depend primarily on the availability of electrical power, discharge pressure requirements, and the volume of air required. Electrical power is generally the most economical means of producing compressed air. Not only are costs per volume of air generally lower than with fuel operated compressors, but electrically run compressors generally need less attention, have fewer mechanical problems, and create less noise. Noise generation by any compressor can be substantial and may require soundproofing depending on location and local

conditions.

A description of procedures for compressor selection and supply line design is given in Appendix C.

Diffuser Design and Bubble Size -- There is some controversy over the proper design of diffusers and desirable bubble sizes. Without further experimental and theoretical work no specific design criteria can be given. In general, small bubbles well dispersed in the upwelling pipe are desirable.

Potential Problems

There are several potential problems with hypolimnion aerators which are briefly discussed below.

Undersized Aeration Capacity -- It is possible to undersize the system either by underestimating the oxygen consumption rate of the hypolimnion and/or by overestimating the amount of oxygen the system will dissolve. In all cases, it is highly desirable to design a larger system than is needed based on best estimates. Oversizing the system will increase its capital costs only slightly, and the operating costs should be equal to a smaller system if the oversized system is operated intermittently.

Unintentional Thermal Destratification -- It is possible to thermally destratify the lake during hypolimnetic aeration if precautions are not taken. Fast (1971) caused Hemlock Lake, Michigan, to destratify early because his hypolimnetic aeration system leaked water. His aerator was constructed of corrugated steel plates which were riveted together. Caulking should have been placed between the plates before fastening. This leakage caused a dense algal bloom since the upwelled water was high in nutrients.

Attica Reservoir, New York, was rapidly destratified by the Side Stream Pumping (SSP) hypolimnetic aeration system even though only 2.6% of the hypolimnetic volume was pumped per day (Fast, 1973b; Matsch, 1973). However, the discharge velocity was very high and this apparently imparted an intolerable momentum to the hypolimnion. The volume pumped per day was later reduced to less than 1% per day but the reservoir still destratified too rapidly (Terry Haines, personal communications, 1976).

Satisfactory thermal stratification was maintained at Ottoville Quarry, Ohio, with the SSP system when 2.6% of the hypolimnetic volume was pumped per day. Nevertheless, Ottoville's hypolimnetic temperature increased greatly during hypolimnetic oxygenation: 9.0°F in 3.5 months during 1973, and 14.4°F in 5 months during 1974 (overholtz, 1975). Ottoville Quarry was 55 feet deep, compared to 31 feet for Attica Reservoir.

Even though most full air lift designs move larger volumes of water compared with the SSP, we know of none other than the Hemlock Lake case where they have caused unacceptable destratification. This is undoubtedly due to their much lower discharge velocities.

Nitrogen Gas Supersaturation --
Certain air injection systems may supersaturate the water with nitrogen gas (N_2) relative to surface hydrostatic pressures. The entire water column is normally at 100% saturation relative to the surface (Hutchinson, 1957), and even a small increase will result in supersaturation. Nitrogen gas saturation in rivers of only 115% or less can cause substantial mortalities of salmon and trout (Rucker, 1972).

According to Speece (1975a) even the full air lift hypolimnetic aerator and destratification air injection systems may cause N_2 supersaturation relative to the surface of 160% or more. We doubt this, but have no evidence to confirm or reject the hypothesis. The only indirect evidence we have is that oxygen concentrations at the top of hypolimnetic aerators (full air lift designs), and oxygen concentrations in the bubble plumes of lake destratification systems seldom if ever exceed 100% saturation. Even if the "influent" water were near zero in dissolved oxygen, we would not expect a very large amount of N_2 to be absorbed. Some N_2 almost certainly would be absorbed as the 0_2 content of the air bubble decreases relative to its N_2 content. This change would increase the partial pressure of N_2 slightly (initially 78%) and thus tend to put more N_2 into the solution. This is one of the most important questions which must be answered before any form of air injection is used in conjunction with tailwater releases.

The Limno hypolimnetic aeration system (partial air lift design, Appendix B) can cause nitrogen gas supersaturation in the hypolimnion of more than 150% relative to surface pressures (Fast, et al., 1975a). Special caution should be used with this system even if there are no tailwater releases. Under some situations, the system might cause N_2 supersaturation even within the hypolimnion or base of the thermocline. The principal reason for this is that the aeration occurs in the hypolimnion and relatively high hydrostatic pressures are maintained at all times.

We know of no fish deaths caused by gas supersaturation with any hypolimnetic aerator/oxygenator, but precautions should be considered.

High Free Carbon Dioxide --
Systems which inject pure oxygen, and in which essentially all the gas is dissolved in the hypolimnion, do not appear to remove much gas such as CO_2. If the water is soft, and is weakly buffered, there could be an excessive accumulation of free CO_2. The added oxygen may increase organic decomposition and thus the generation of CO_2. There was not an unacceptable increase in free CO_2 at Ottoville Quarry even during 5 months of oxygenation by the SSP process, but the quarry was a former limestone quarry with well buffered, hard waters.

Water Level Fluctuations --
Many of the hypolimnetic aerators described in Appendix B are not well suited to accomodate large vertical changes in the water levels. Some can be designed with telescoping parts, but they are most efficient and least costly to build in lakes with relatively stable water levels. If the water level fluctuation is too drastic, there may not be much of a hypolimnetic volume at the lower level, and no system would be appropriate.

SECTION IV

EXAMPLES OF METHODOLOGY APPLICATION

INTRODUCTION

The purposes of this section are to provide a comparison of results with the procedures described here and also to illustrate the application of the procedures to an example lake.

PAST EXPERIENCE

Although a number of aeration/circulation systems have been used in various parts of the world, there are very few for which sufficient data are available to evaluate the adequacy of procedures described in this document. However, the procedures were found to be consistent with observations from those few systems for which sufficient data were readily available.

Kezar Lake

Kezar Lake in New Hampshire is a eutrophic recreational lake of 182 acres (8×10^6 ft^2) with a maximum depth of 30 feet and mean depth of 10 feet. As a result of nuisance algal blooms the New England Regional Commission funded a project to demonstrate the control of algae by artificial mixing. The project was carried out by the New Hampshire Water Supply and Pollution Control Commission. Kezar Lake was effectively destratified (nearly uniform vertical algal profiles maintained) with the release of approximately 100 SCFM of air at a depth of 27 feet. The air was discharged at 13 psi from four shore placed Curtiss CW-808 air compressors through approximately 1000 feet of 2 inch PVC pipe and 12 stone diffusers.

The design "rule of thumb" of 30 SCFM per 10^6 square feet of Lake surface would have indicated 240 SCFM would be needed for total mixing. Good mixing was probably achieved with the smaller air flow rate due to shallow depth and exposure to wind mixing.

The effects of mixing on algal production were found to be consistent with the procedures described here. Lorenzen and Mitchell (1975) provided an evaluation of this project and compared observed values of peak algal biomass to predicted values. The results, shown in Figure IV-1 were compatible.

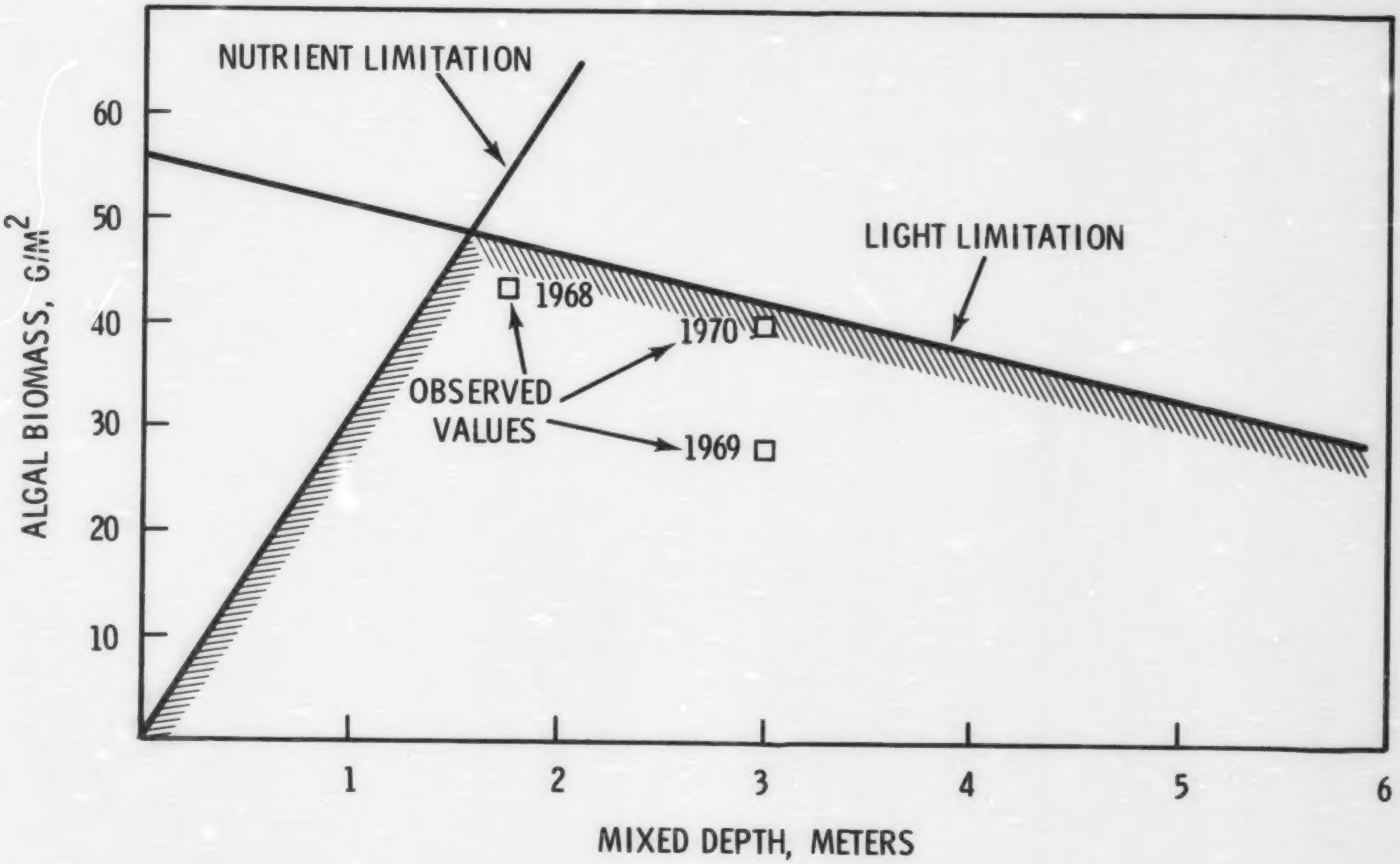


Figure IV-1. Theoretical and observed peak biomass in Kezar Lake, 1968 stratified; 1969 and 1970 artificially destratified.

El Capitan Reservoir

The chemical and physical characteristics of El Capitan Reservoir, California have been described in detail by Fast (1968). The reservoir impounds the intermittently flowing San Diego River.

The reservoir area and volume fluctuate with changes in surface elevation. However, the mean depth is approximately 30 feet and the surface area 21 x 10^6 square feet. Thermal stratification usually begins in March or April and disappears in November or December.

The reservoir was artificially aerated during 1965 and 1966 with approximately 215 SCFM of air discharged at approximately 60 psi from a shore installed Le Roi 50-S-2 compressor driven by a 50 horsepower electric motor. The air was released through 90, 1/8 inch diameter holes in 100 feet of 1-1/2 inch PVC pipe at a depth of approximately 80 feet.

This system did not destratify the reservoir and rates of algal production were increased. No biomass measurements were made. This increase was apparently due to a lessening of the mixed depth which is consistent with the theory used here. It is estimated that significantly more air (30 x 21 = 630 SCFM) would be required to adequately mix El Capitan Reservoir.

San Vicente Reservoir

An aeration system has not been installed in San Vicente Reservoir. However, some cost estimates have been made (Fast, *et al*., 1976) and some data are available. This example was chosen to illustrate the procedures for evaluation.

San Vicente Reservoir is the major domestic water supply reservoir for the City of San Diego. The reservoir stores a small amount of direct runoff, but most of its water is imported, primarily from the Colorado River. It is a warm monomictic lake. Thermal stratification typically begins in March or April, and may extend through December or even into January. The maximum volume, depth, and surface area are 90,000 acre-feet, and 190 feet, and 1000 acres respectively. Oxygen depletion rates are known to vary considerably from year to year. However, data taken during 1973 will be used for this example.

Thermal and chemical stratification developed in San Vicente during April, 1973 at which time surface temperatures were 59°F and bottom temperatures were 55°F (Figure IV-2). The thermocline was not well defined, but oxygen

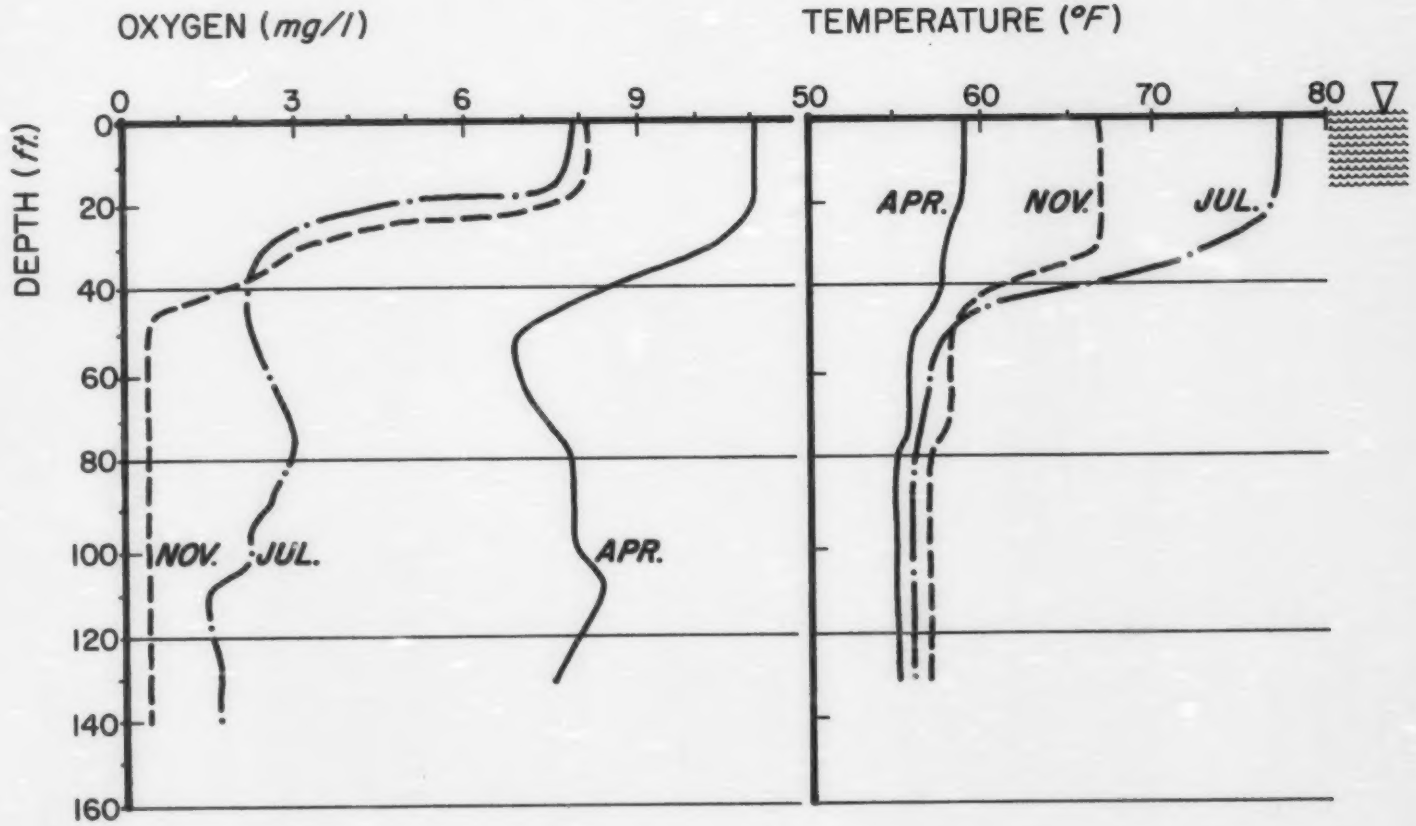


Figure IV-2. Temperature and oxygen profiles in the San Vicente Reservoir.

concentrations decreased sharply from 11 mg/ℓ at 20 feet to 7 mg/ℓ at 50 feet. During July the thermocline was well defined and extended from 25 to 50 feet. Hypolimnetic oxygen had decreased from 7.5 mg/ℓ in April to less than 3 mg/ℓ. During November surface waters had cooled to 67°F, but the thermocline was still well defined between 30 and 50 feet. Hypolimnetic oxygen had decreased to an average 0.5 mg/ℓ. These data yield an oxygen depletion rate of slightly less than 1 mg/ℓ/month, and a thermocline range of 25 to 50 feet during mid-summer.

Water depths ranged between a low of 170 feet in January to a high of 184 feet in August. Maximum water volume was 84,021 acre-feet. The base of the thermocline was 50 feet without aeration during 1973. However, we will assume that it would be raised to the 40 foot depth during aeration. The hypolimnetic volume was approximately 47,720 acre-feet ($62.9 \times 10^9 \ell$).

Hypolimnion Aeration --

Following the procedures outlined in Chapter III, the oxygen requirements are estimated to be:

Oxygen Required --

$$\frac{(1.5\ \text{mg}/\ell/\text{month})}{30\ \text{days/mo.}} \times 62.9 \times 10^9\ \ell = 3.145 \times 10^6\ \text{g/day}$$

Minimum Air Flow (100% O_2 transfer efficiency) --

Air at 21% O_2 = 8.2 gO_2/ft^3

$$\frac{3.145 \times 10^6\ \text{g/day}}{8.2\ \text{g/ft}^3} = 370{,}000\ \text{ft}^3\text{/day} = \underline{\underline{256\ \text{SCFM}}}$$

Air Flow Based on Saturation --

Water temperature = 55°F

Required O_2 = 5 mg/ℓ

Saturation at 55°F = 9.5mg/ℓ

Increase = 9.5 - 5.0 = 4.5 mg/ℓ

$$\text{Water Flow} = \frac{3.145 \times 10^{6} \text{ g/day}}{4.5 \times 10^{-3} \text{ g/}\ell} = 699 \times 10^{6} \ \ell\text{/day}$$

$Q_w = 283$ cfs

See Appendix D, Figure D-2 (for 150 foot depth).

Diameter	Q_w^3/Q_a	Q_a
6 feet	7.5×10^5	$\Longrightarrow$ 1800 SCFM
7	1.4×10^6	$\Longrightarrow$ 968
8	2.4×10^6	$\Longrightarrow$ 565

An eight foot diameter upwelling pipe with 565 SCFM of air supplied at the 150 foot depth should be sufficient.

Based on a 300 foot, 2 inch diameter supply line, the pressure required at the compressor discharge (following filter and oil removal devices) would be (See Appendix C):

$$P = h_\ell + \Delta P + \text{depth} \ \frac{14.7}{33} \qquad \text{(IV-1)}$$

where: $h_\ell \simeq 6$ psi (CRANE nomographs)

$\Delta P = 5$ psi (trial value)

$150 \ \frac{14.7}{33} = 67$ psi

$P = 6 + 5 + 67 = 78$psi

A compressor to deliver 565 SCFM at 80 psi would require approximately 115 horsepower. Approximately 50, 1/8 inch diameter orifices would be required to relase the 565 SCFM of air at the bottom of the upwelling pipe (see Section II).

Destratification --

San Vicente Reservoir has a surface area of approximately 1000 acres (44×10^6 ft^2). According to the rule of thumb established in Section II, approximately (30 x 44) = 1320 SCFM of air would be required for destratification. There are not sufficient data to determine the effects of destratification on algal production. However, if thorough mixing to a depth of even 60 feet could be achieved, very low algal concentrations could be maintained.

Cost Estimating --

Hypolimnion Aeration --

The major capital cost items for hypolimnion aeration systems will be:

- Device
- Compressor
- Air Supply Lines and Diffusers

The actual device could be a simple upwelling-downwelling pipe such as shown in Figure B-5, in Appendix B. Fast, et al., (1975c) estimated capital costs to be on the order of $200,000 for such a system. Various patented systems described in Appendix B could also be used. Local suppliers should be asked for prices on the described simple systems to provide a comparison to price quotations for patented systems.

Operating costs will be primarily for electricity. The example system with a 115 horsepower motor operated 6000 hours per year would consume approximately 575,000 kw-hours. At $0.03 per kw-hour this would be $15,500 per year.

Destratification --

The major capital cost items associated with a destratification system would be:

- Air Compressors
- Supply Line
- Diffuser

Two complete air compressors, motors, and associated appurtenances to deliver 1200 SCFM of air would cost on the order of $50,000-$60,000. Supply line and diffusers would be approximately $5,000.00.

Power costs would be approximately double those for the suggested hypolimnion aeration system or $31,000.00 per year.

SECTION V

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SECTION VI

APPENDIX A

LAKE MODEL COMPUTATIONS

The basic model used for computation of temperature and algal profiles for various levels of induced mixing is based on the Lake Ecologic Model originally developed by Chen and Orlob (1975). The model was modified for this application to compute only temperature and algal growth. Two types of algae were simulated; one neutrally bouyant and one with a rise velocity of 2 feet per day.

The purpose of the model application was solely to simulate the effects of imposed mixing on the vertical profiles of temperature and algae.

Physical Representation

Each lake simulated was idealized as a number of horizontally mixed layers. Natural vertical mixing is computed by the use of dispersion coefficients in the vertical mass transport equation. Values of the dispersion coefficients for different size lakes were estimated from previous studies (Water Resources Engineers, Inc., 1969).

Temperature

Temperatures as a function of depth were computed according to equation A-1.

$$\bar{V} \frac{\partial T}{\partial t} = \frac{1}{c\rho} \frac{\partial}{\partial z} \left(A_z D_z \frac{\partial T}{\partial z}\right) - \frac{\partial}{\partial z} (QT) + \frac{A_s}{c\rho} (\mu - \lambda T) + \frac{\Theta}{c\rho} - T \frac{\partial \bar{V}}{\partial t} \quad \text{(A-1)}$$

where: T = the local water temperature

c = specific heat

ρ = fluid density

A_z = cross-sectional area at the fluid element boundary

D_z = the eddy diffusion coefficient in the vertical direction

Q = advection across the fluid element boundaries

A_s = cross-sectional area of the surface fluid element

$\mu\lambda$ = coefficients describing heat transfer across air water interface

Θ = sum of all external additions of heat to fluid volume of fluid element

$\bar{v}$ = element volume

To assure comparability between simulation the same weather conditions were used for all cases.

Algal Growth

Because only the vertical distribution of algae was of interest, algal growth rates were assumed to be only a function of available light and temperature. Nutrient dependence was not considered.

Algal concentrations as a function of depth were computed according to equation A-2.

$$\bar{v}\frac{\partial P}{\partial t} = \frac{\partial}{\partial z}\left(A_z D_z \frac{\partial P}{\partial z}\right) - \frac{\partial}{\partial z}(QP) - P\frac{\partial \bar{v}}{\partial t} + P\,(PG-PR)\,\bar{v} - \frac{\partial}{\partial z}(PA_z)\,PS \qquad \text{(A-2)}$$

where: P = the algal concentration

PG = the algal growth rate

PG = PMAX $\left(\frac{LI}{L_2 + LI}\right)$

PMAX= the maximum specific growth rate of algae at 20°C

LI = the available light energy

L_2 = the half saturation constant for algae utilizing light energy

PR = the algal respiration rate

PS = the algal settling rate

Q = vertical advective flow

Light intensity as a function of depth was computed from the relationship:

$$LI = I_o e^{(-\alpha + \beta P)d} \qquad \text{(A-3)}$$

where: I_o = surface light

α = extinction coefficient

β = incremental extinction coefficient due to algae

d = depth

The algal growth rate parameters used were:

Parameter	Value	
	Alga 1	Alga 2
PMAX	1.0	1.0/day
PR	0.15	0.15/day
PS	0	-0.5 m/day
L_2	0.03	0.03 langley
α	0.7	0.70 m^{-1}
β	0.2	0.2 m^{-1}/mg/ℓ

Imposed Mixing

The theory of Kobus (1972) indicates that upwelling flow can be computed if the air release rate and depth are known. His relationship was used to compute an incremental vertical flow for each layer. The total flow reaching the top element was then evenly distributed from the top element down to the element with a density equal to the mixture of upwelled water. This procedure is diagramatically illustrated in Figure A-1.

Application-Verification

The model was applied to Kezar Lake in New Hampshire and El Capitan Reservoir in California to verify that artificial mixing could be adequately simulated.

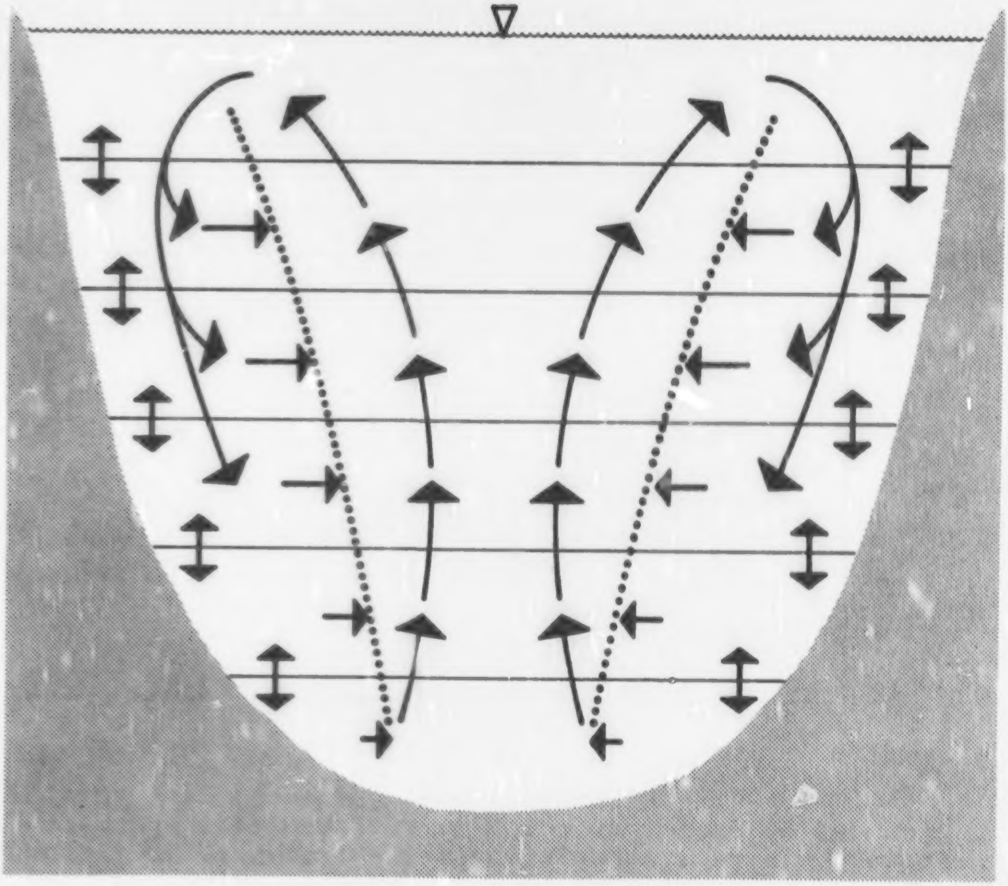

Figure A-1. Diagramatic representation of air induced vertical mixing.

Computed temperature profiles are compared to observed values in Figures A-2 and A-3. The model performance was judged to be good for the intended purpose of providing guidance. However, it is recommended that for any large scale application, a simulation model be applied to the specific lake in question.

Test Cases

This modeling procedure was applied to fourteen hypothetical lakes listed in Table A-1. The range of depths and volumes was intended to cover most probable situations. For each lake, the model was run using the same weather conditions. The temperature and concentrations of each alga in each layer were computed on a daily basis for 180 days. The maximum difference between top and bottom temperatures and algal concentrations that occurred during the simulation period were then used to assess the degree of mixing. Figure A-4 shows the results obtained for Kezar Lake with and without aeration.

Each lake simulation was repeated with different air release rates. The concentration and temperature differences were then plotted as a function of air release rate for each lake. Figures A-5 through A-18 show the results. The value of ΔT represents the maximum difference between surface and bottom temperatures computed over the 180 day period. The value of ΔC represents the maximum difference between surface and bottom algal concentrations for each of the two algae.

It was found that, for the conditions simulated, the air required in standard cubic feet per minute increased nearly linearly with area and was nearly independent of lake depth (of course, the energy is greater than that required for a shallow lake).

As a "rule of thumb" it was found that approximately 30 (20-40) SCFM of air per 10^6 ft^2 of lake surface area should provide good mixing. This number could be reduced for shallow lakes exposed to extensive wind mixing and should be increased for warmer climates which tend to increase stability.

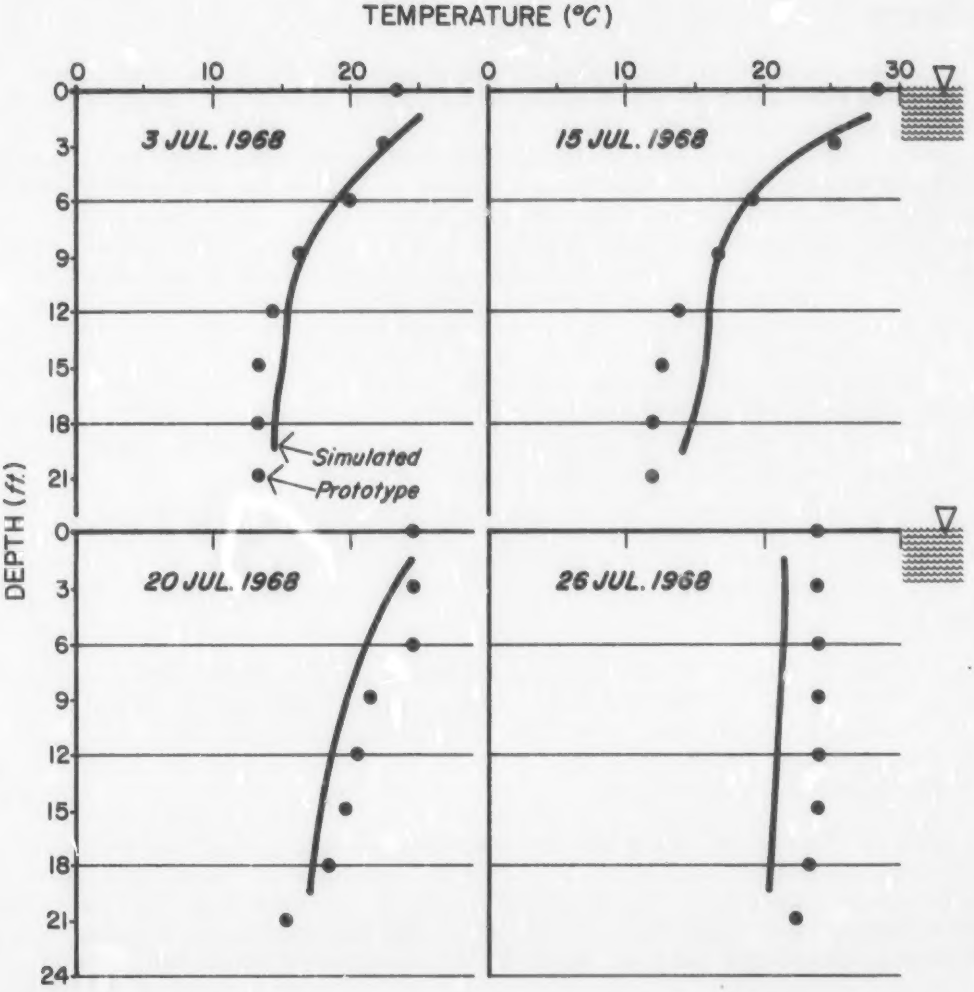

Figure A-2. Comparison of computed and observed temperature profiles in Kezar Lake.

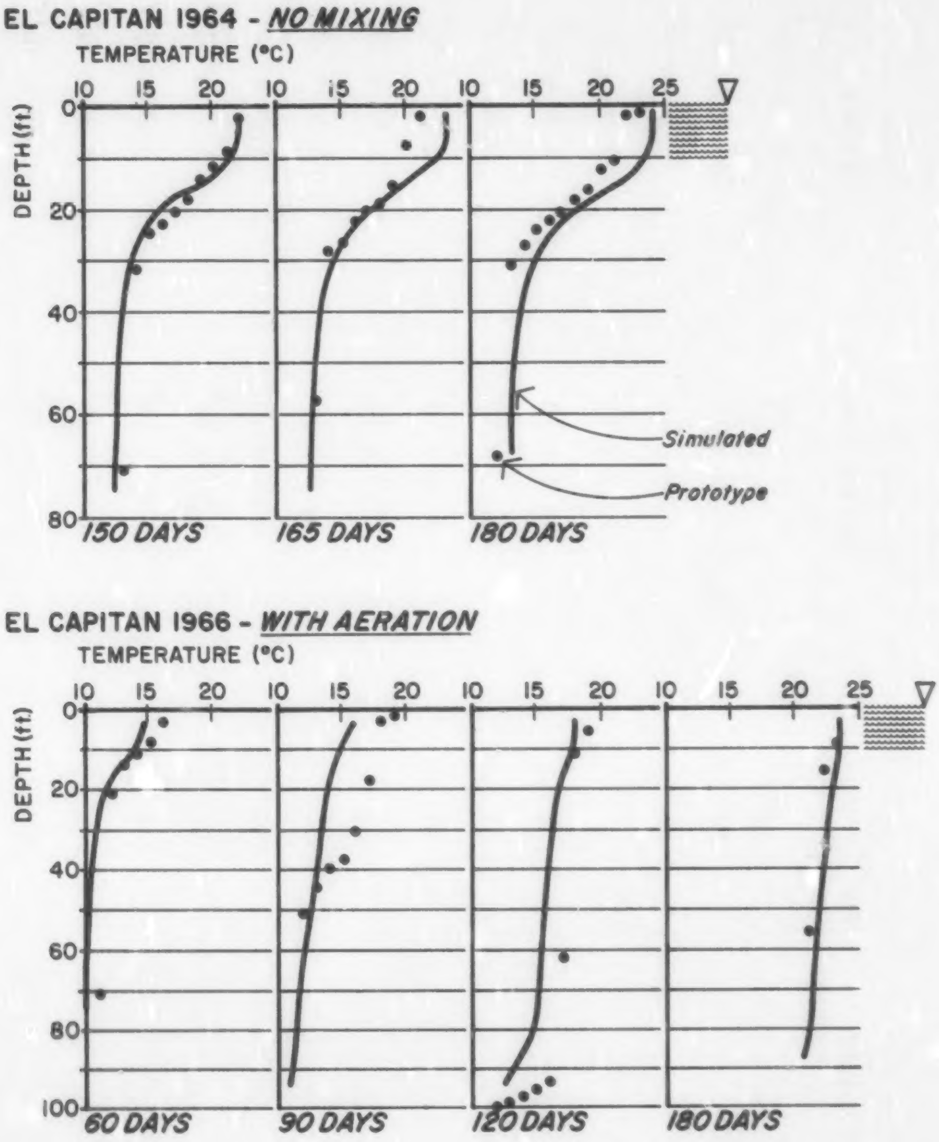

Figure A-3. Comparison of computed and observed temperature profiles in El Capitan Reservoir.

TABLE A-1. GEOMETRY OF LAKES SIMULATED WITH RESERVOIR MODEL

Lake	Avg. depth, (ft)	Max. depth, (ft.)	Surface area, (ft^2)	Volume, (ft^3)
1	9.7	21	7.47×10^6	7.23×10^7
2	9.7	21	1.49×10^7	1.45×10^8
3	9.7	21	2.99×10^7	2.89×10^8
4	9.7	21	7.47×10^7	7.22×10^8
5	26	51	1.71×10^7	4.41×10^8
6	26	51	3.42×10^7	8.80×10^8
7	26	51	8.55×10^7	2.21×10^9
8	26	51	2.14×10^8	5.52×10^9
9	50	100	4.26×10^7	2.10×10^9
10	50	100	1.07×10^8	5.24×10^9
11	50	100	2.66×10^8	1.31×10^{10}
12	50	100	1.07×10^9	5.24×10^{10}
13	93	200	2.07×10^8	1.92×10^{10}
14	93	200	8.28×10^8	7.66×10^{10}

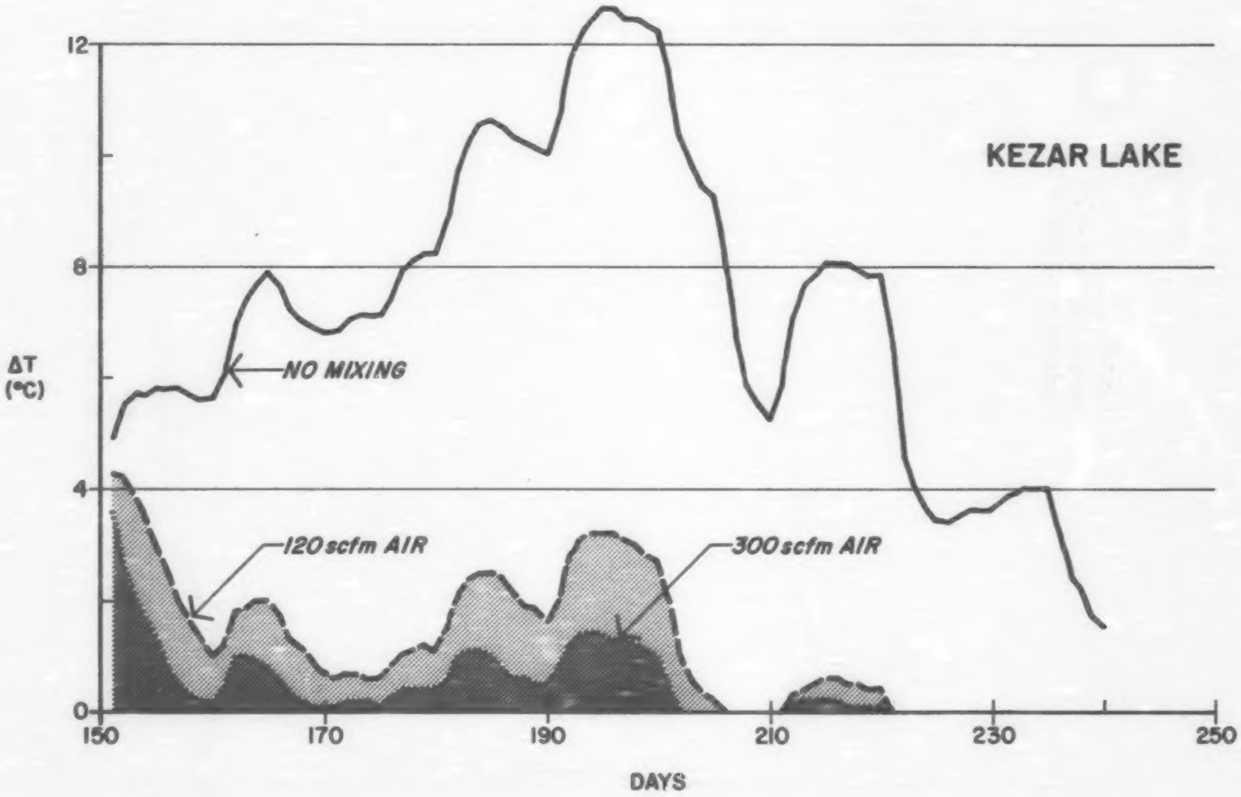

Figure A-4. Computed effects of mixing on temperature stratification in Kezar Lake.

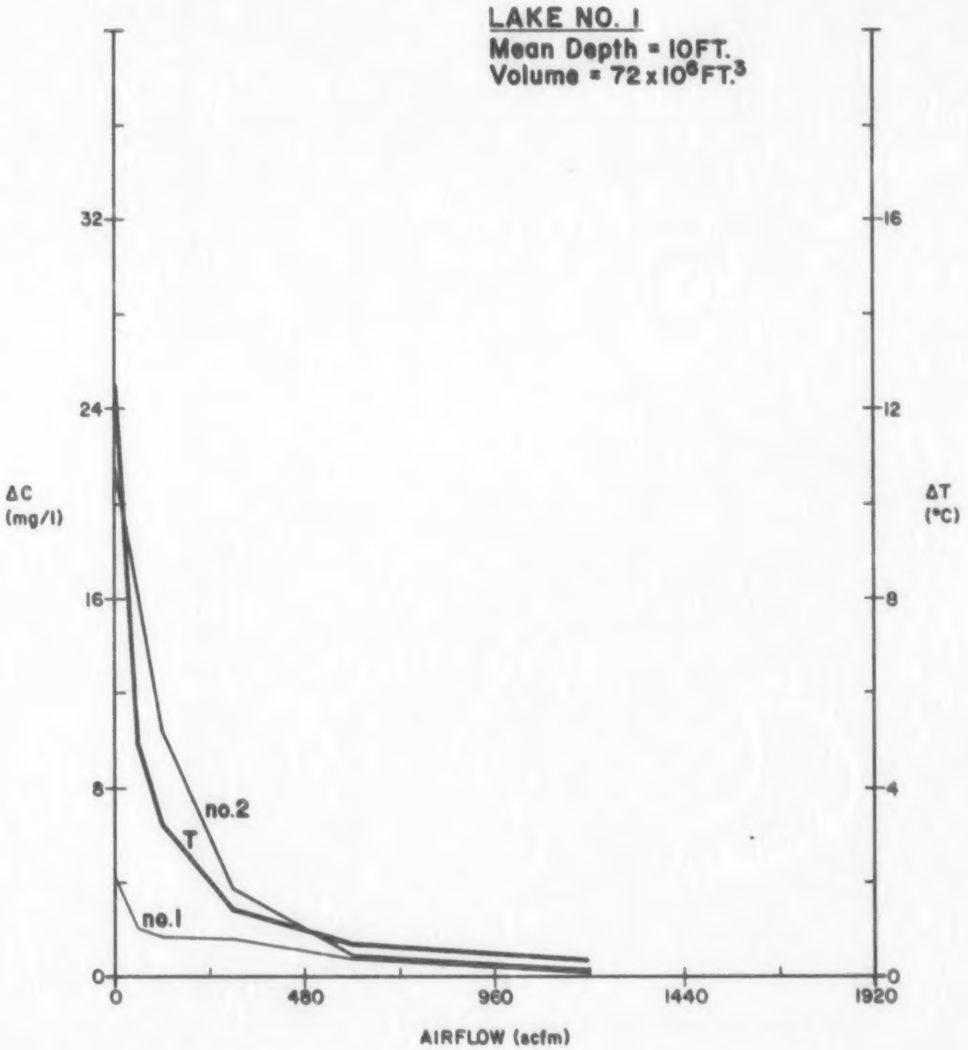

Figure A-5. Computed effects of induced mixing on temperature and algal stratification in hypothetical lake no. 1.

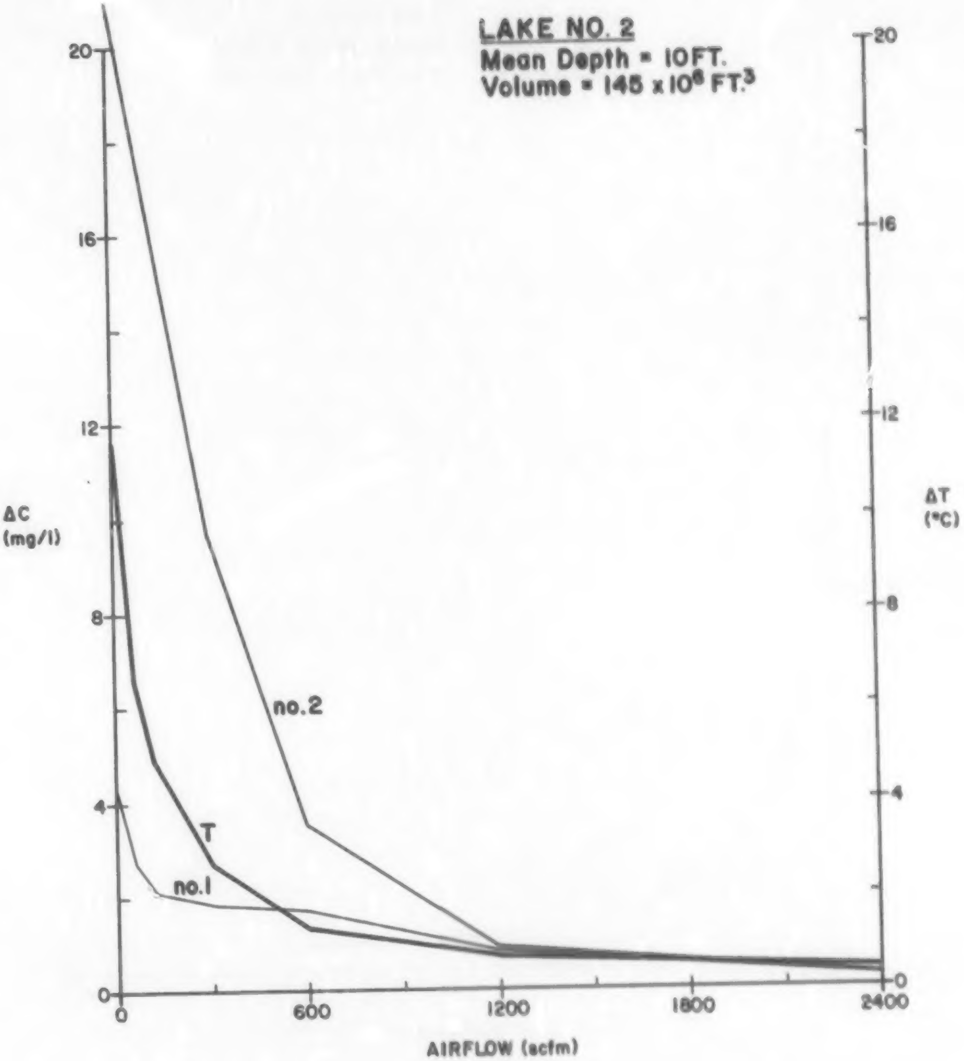

Figure A-6. Computed effects of induced mixing on temperature and algal stratification in hypothetical lake no. 2.

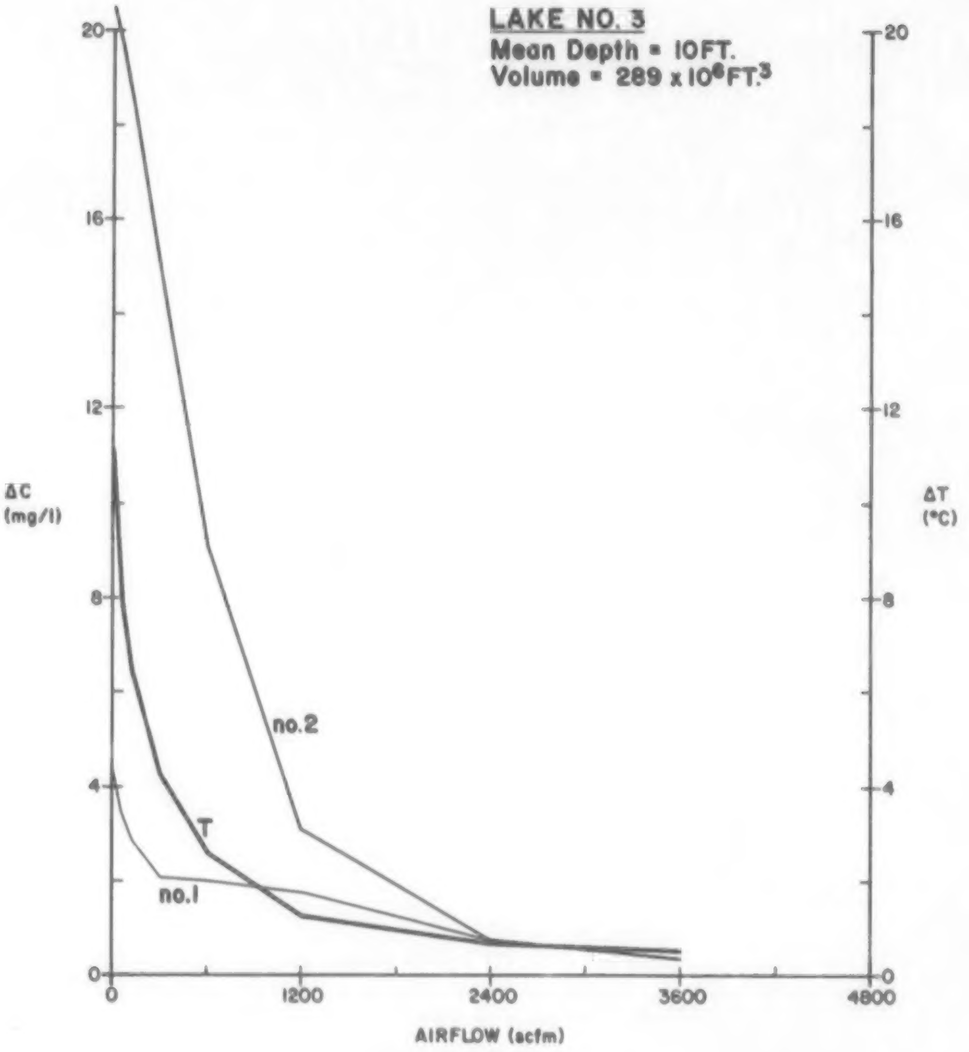

Figure A-7. Computed effects of induced mixing on temperature and algal stratification in hypothetical lake no. 3.

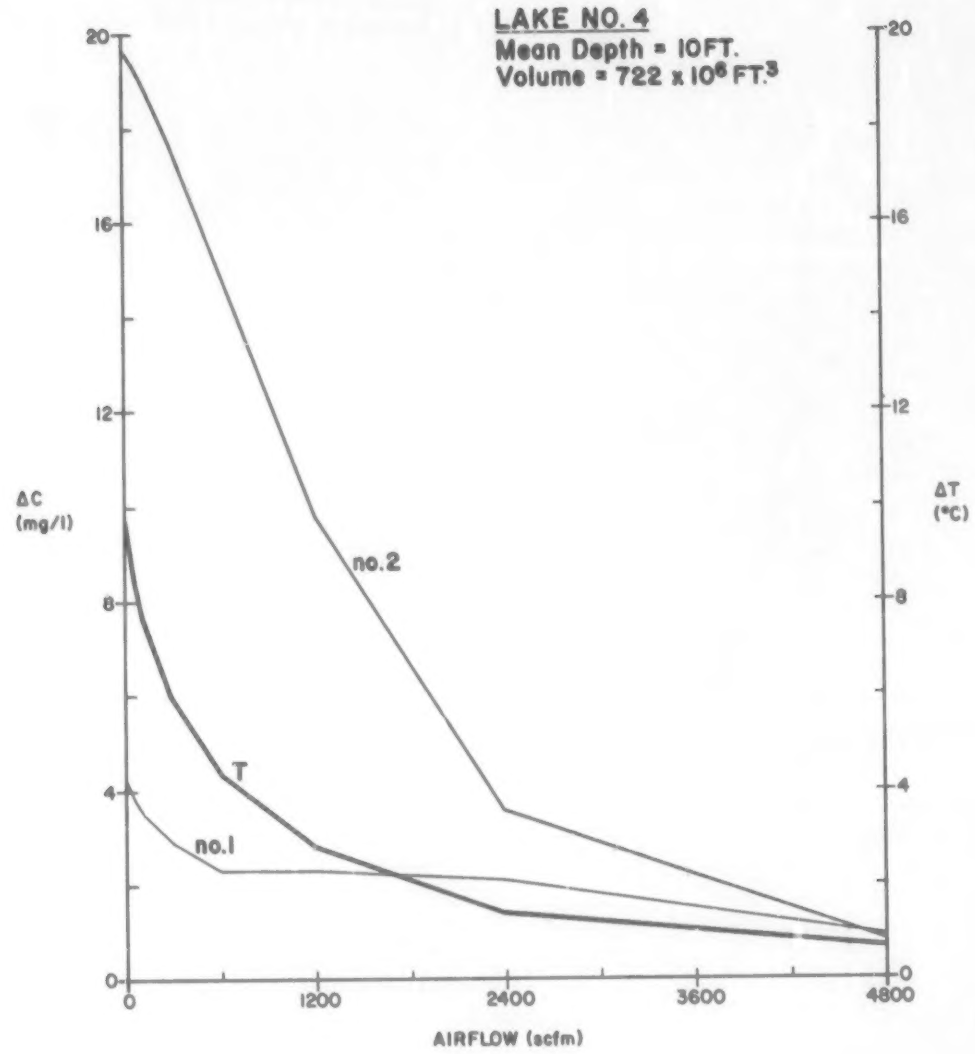

Figure A-8. Computed effects of induced mixing on temperature and algal stratification in hypothetical lake no. 4.

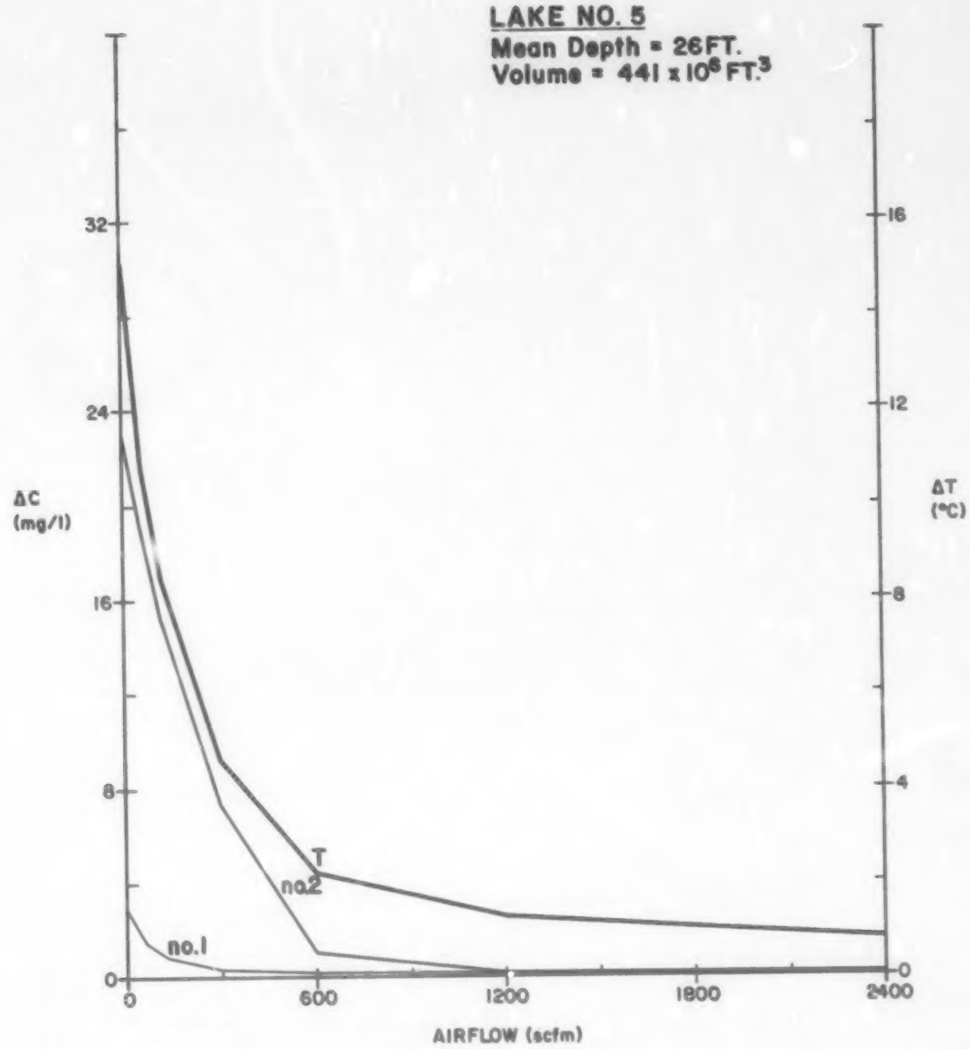

Figure A-9. Computed effects of induced mixing on temperature and algal stratification in hypothetical lake no. 5.

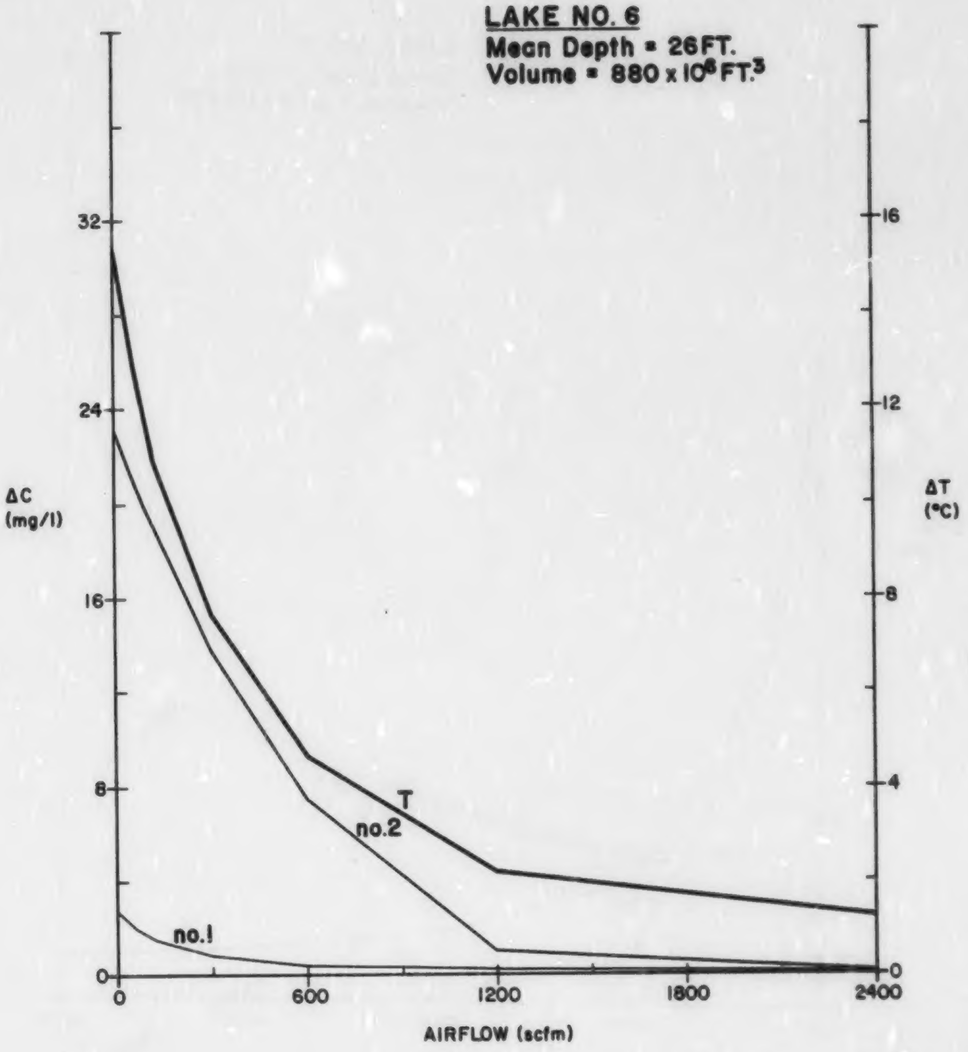

Figure A-10. Computed effects of induced mixing on temperature and algal stratification in hypothetical lake no. 6.

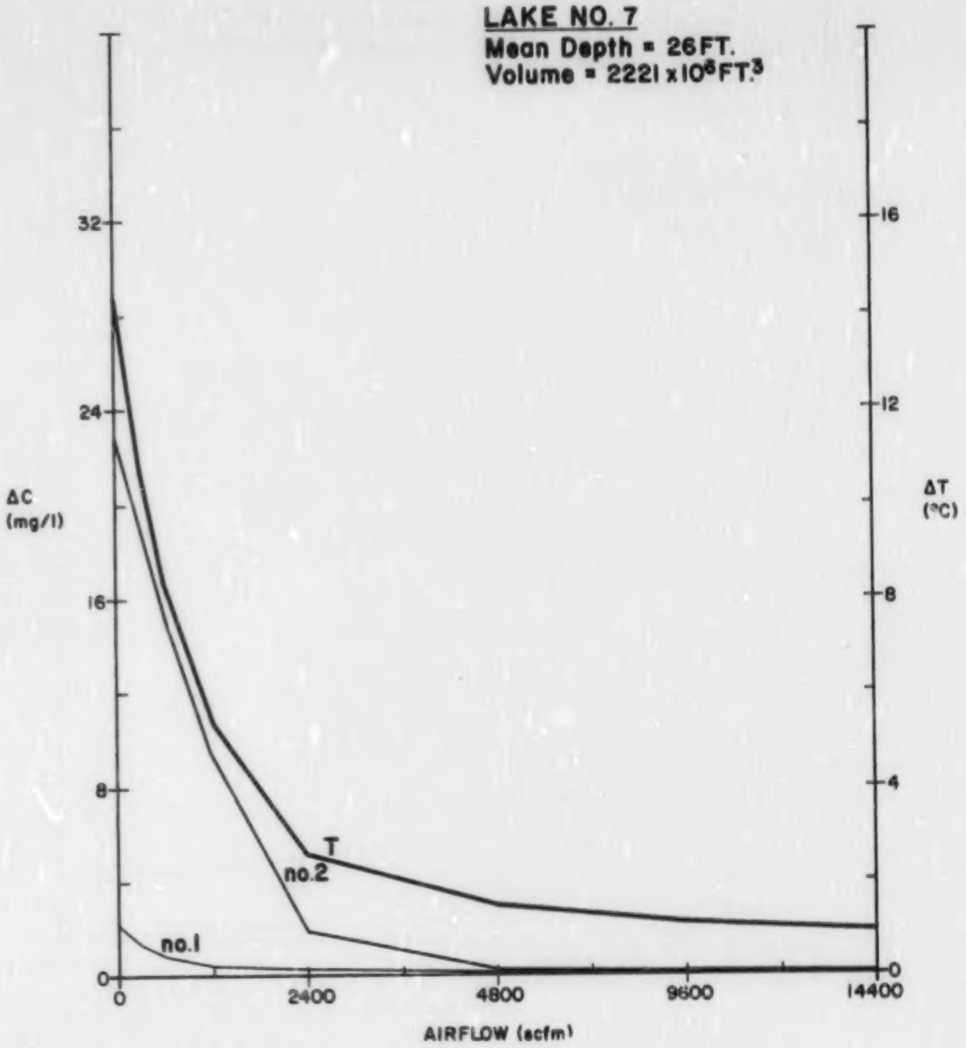

Figure A-11. Computed effects of induced mixing on temperature and algal stratification in hypothetical lake no. 7.

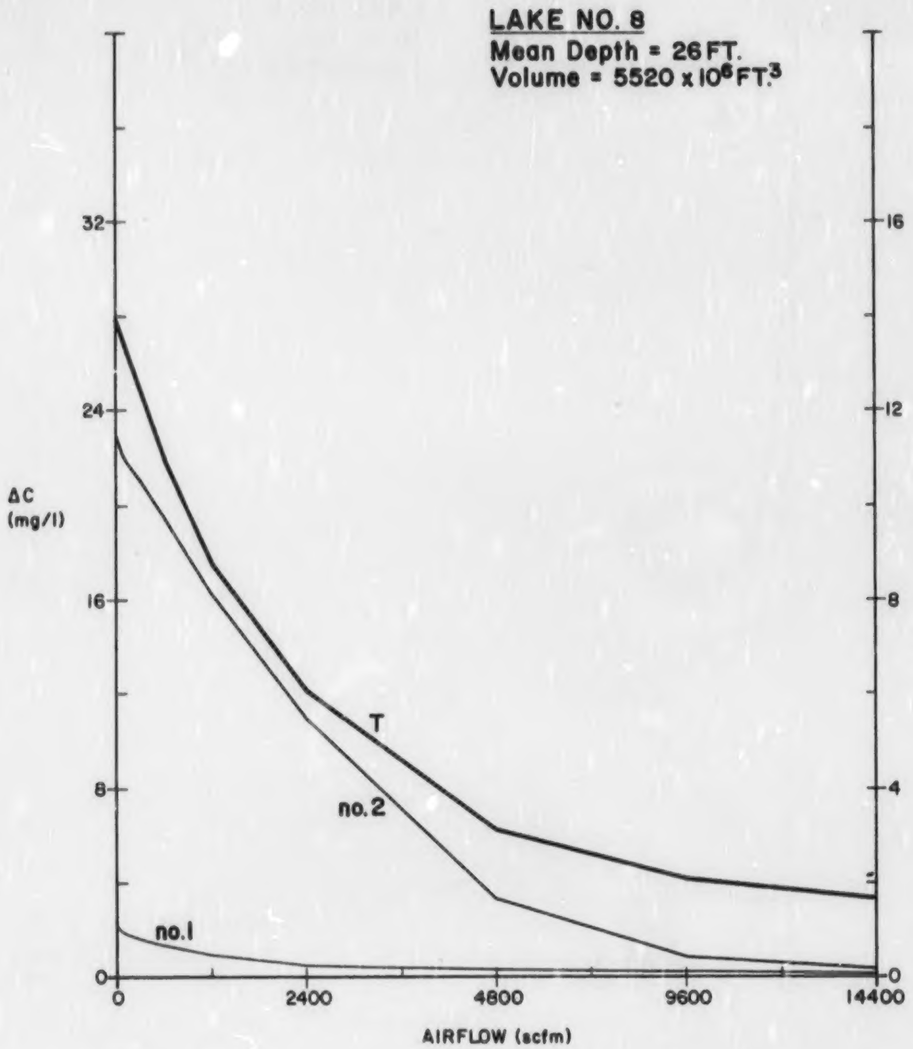

Figure A-12. Computed effects of induced mixing on temperature and algal stratification in hypothetical lake no. 8.

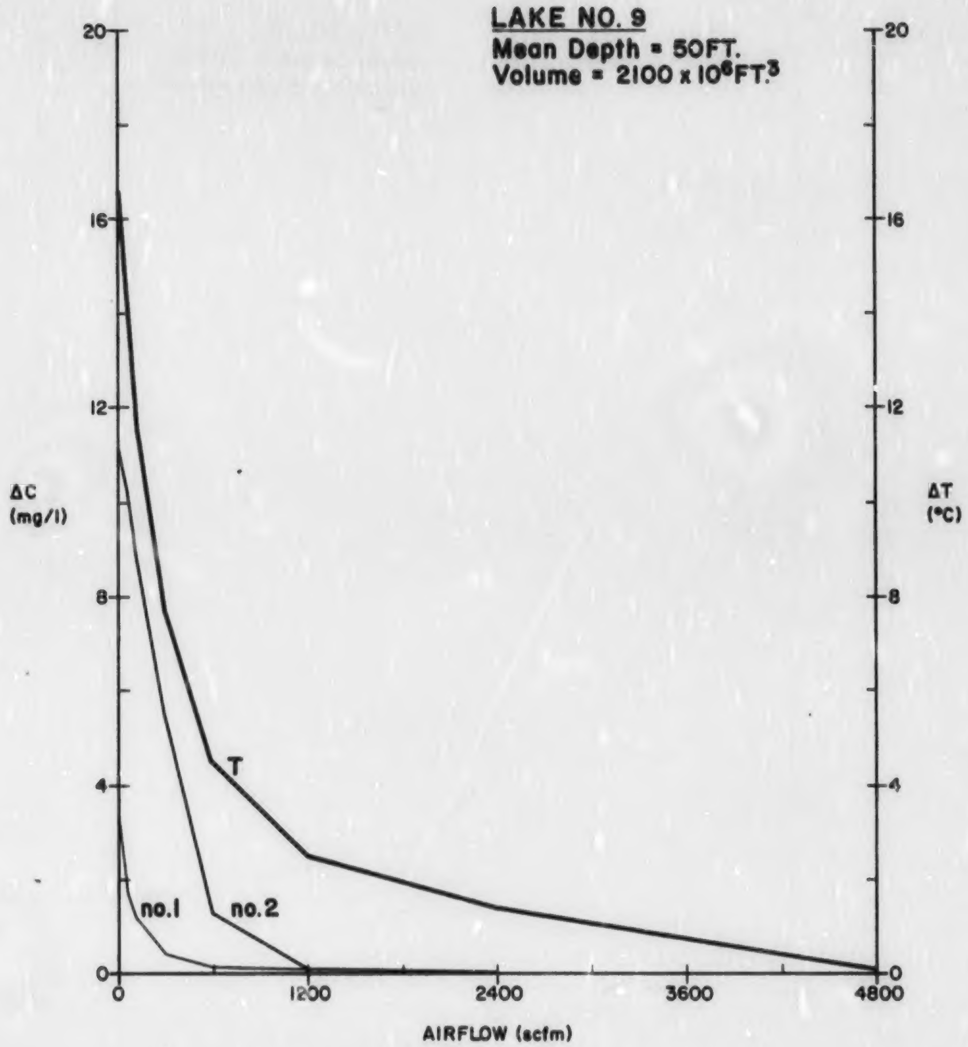

Figure A-13. Computed effects of induced mixing on temperature and algal stratification in hypothetical lake no. 9.

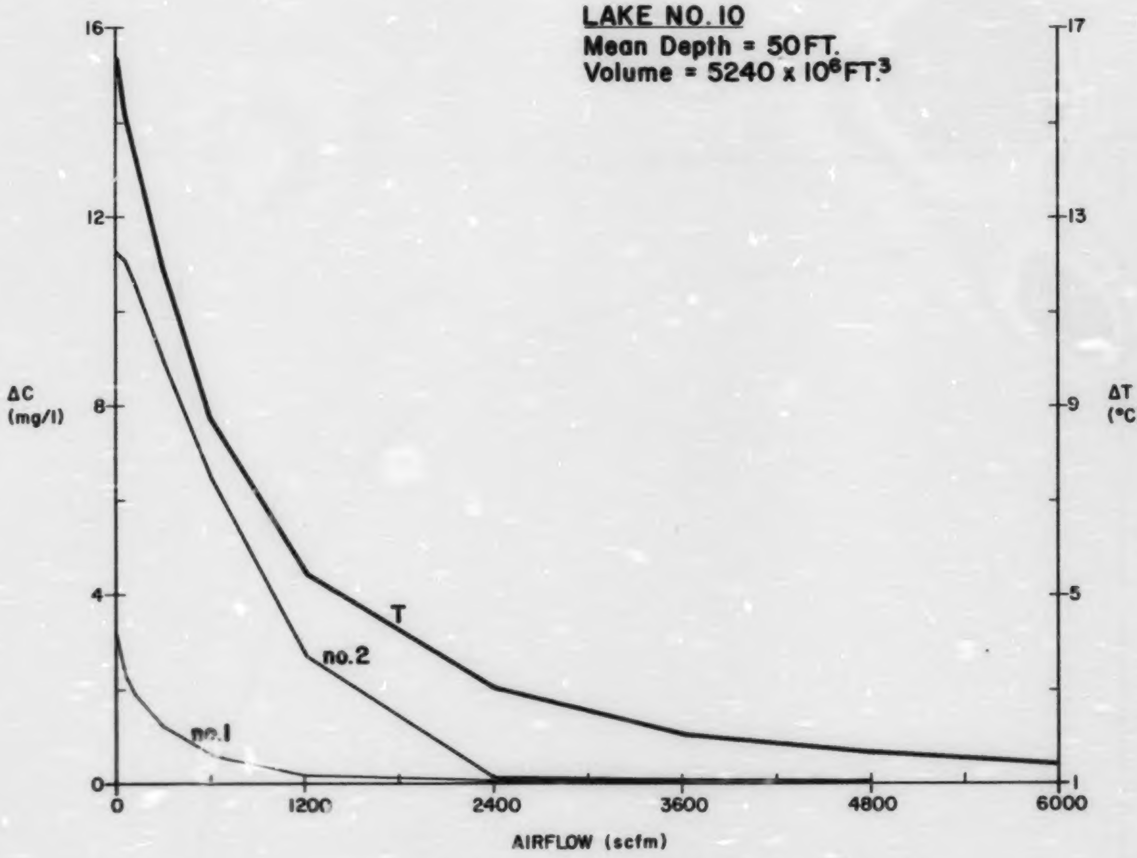

Figure A-14. Computed effects of induced mixing on temperature and algal stratification in hypothetical lake no. 10.

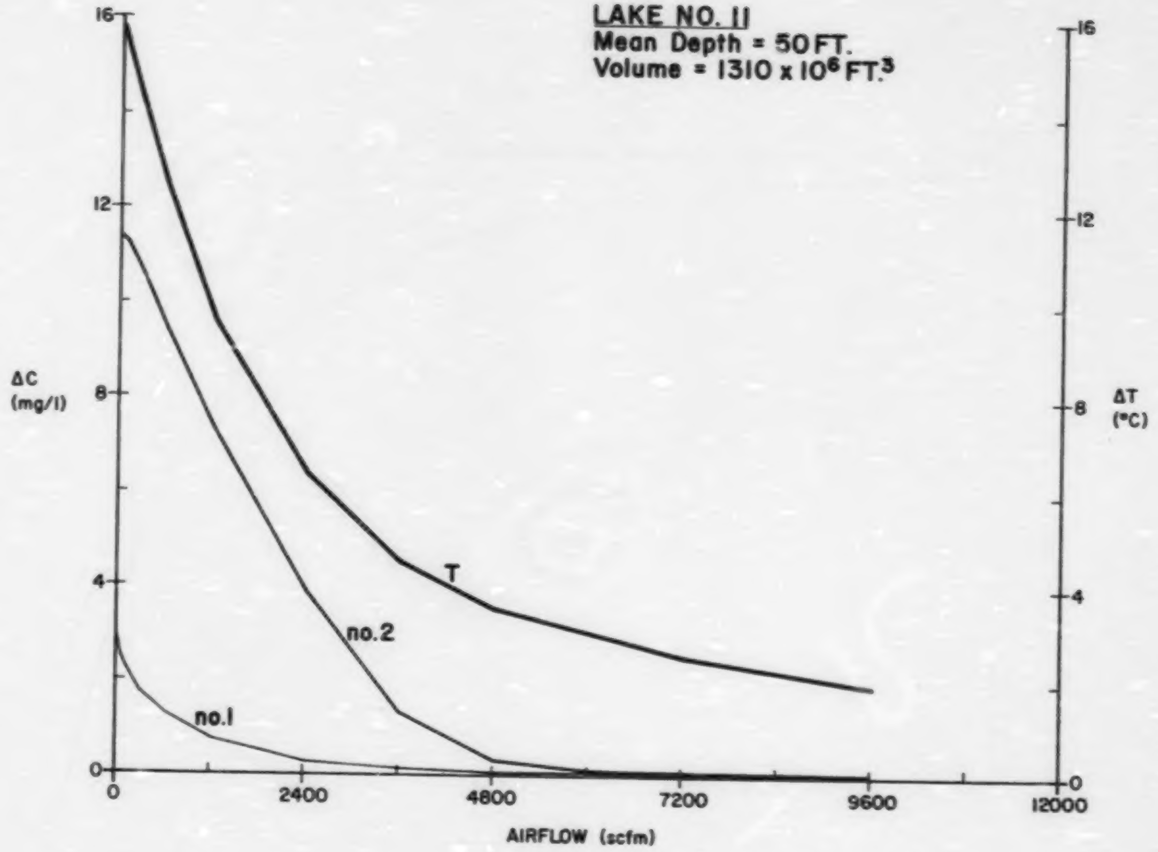

Figure A-15. Computed effects of induced mixing on temperature and algal stratification in hypothetical lake no. 11.

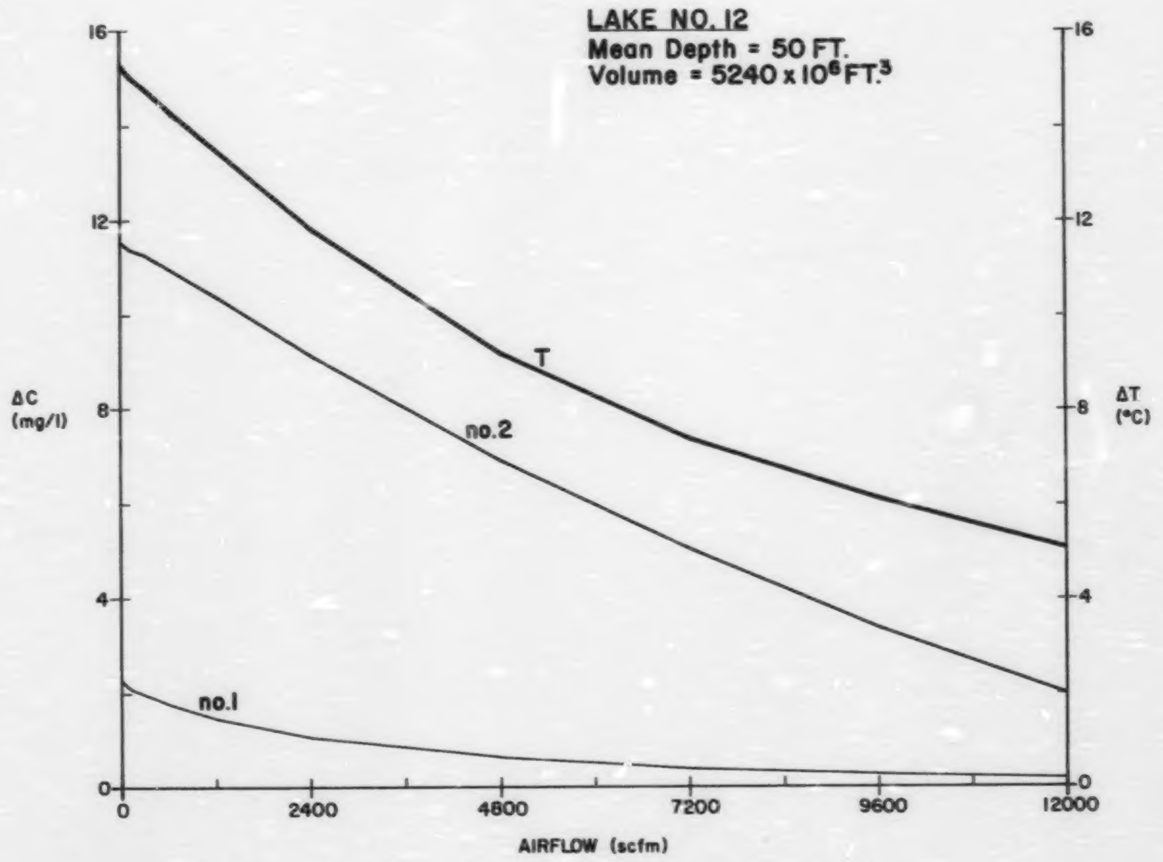

Figure A-16. Computed effects of induced mixing on temperature and algal stratification in hypothetical lake no. 12.

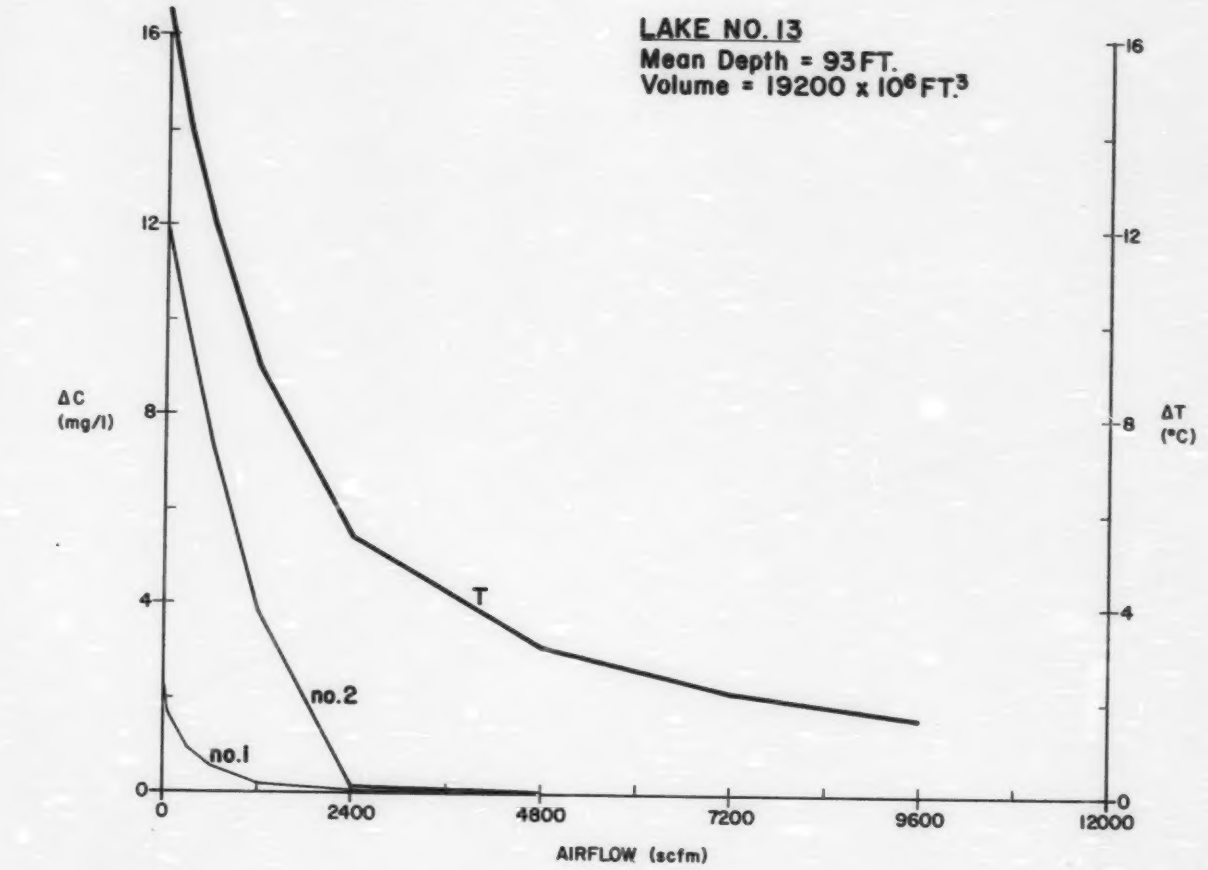

Figure A-17. Computed effects of induced mixing on temperature and algal stratification in hypothetical lake no. 13.

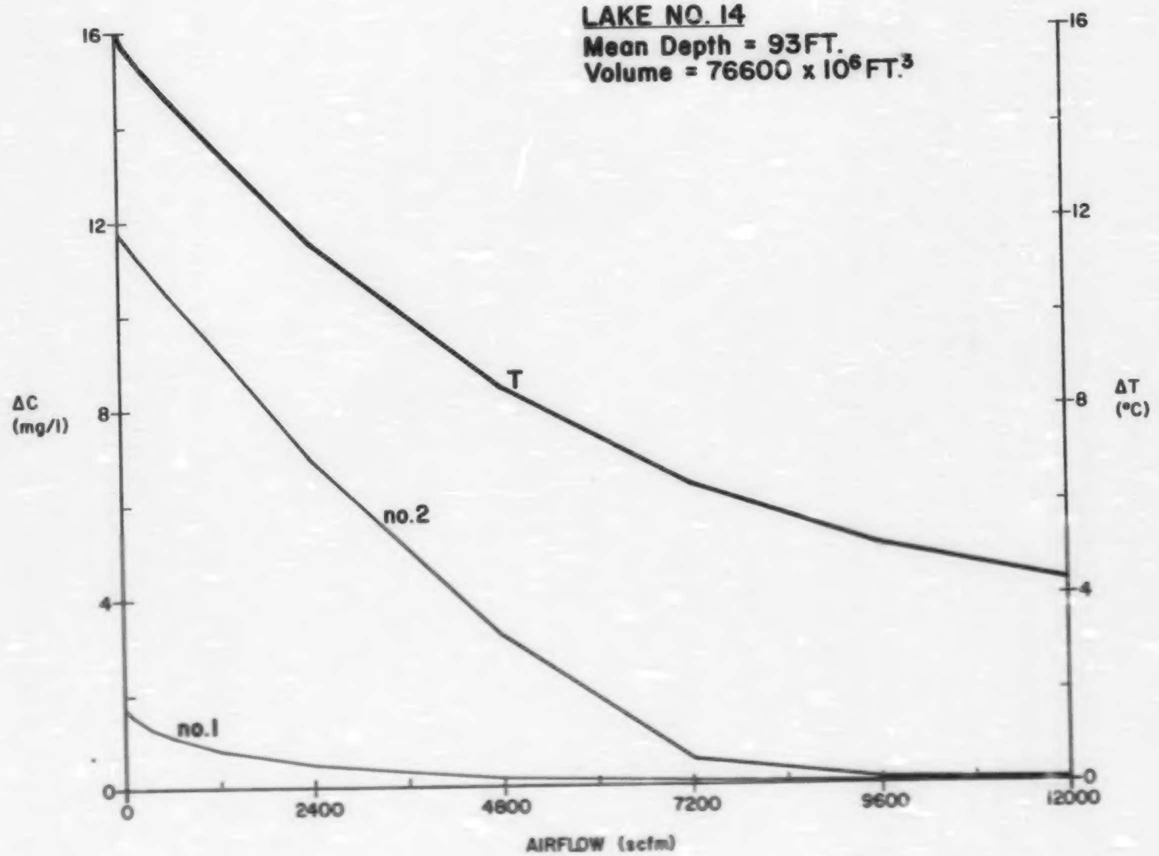

Figure A-18. Computed effects of induced mixing on temperature and algal stratification in hypothetical lake no. 14.

SECTION VII

APPENDIX B

HYPOLIMNETIC AERATION/OXYGENATION

A wide variety of hypolimnetic aeration/oxygenation systems have been proposed and/or tested. At least 21 designs have been proposed and 13 of these have been subjected to full scale testing. These systems add oxygen to the hypolimnion by mechanical agitation, air injection or injection of high purity oxygen. Although this variety of systems exist, no system is in widespread use. There are not sufficient data to thoroughly evaluate all of the systems. The purpose of this appendix is to provide a summary of these systems with performance data when available.

HYPOLIMNETIC AERATION/OXYGENATION DEVICES

Mechanical Agitation System

Hypolimnetic aeration was first reported for Lake Bret, Switzerland, where hypolimnetic waters were aerated by mechanical means (Mercier and Perret, 1949; Mercier and Gay, 1954; Mercier, 1955). Water was withdrawn from the hypolimnion through an intake pipe, and discharged into a splash basin on shore where it was aerated (Figure B-1). The aerated water then returned to the hypolimnion through a discharge pipe by gravity flow. This system is relatively inefficient in terms of oxygen absorbed/kw-hr, but it successfully reduced hypolimnetic iron concentrations in Lake Bret and greatly improved water quality.

Air Injection Systems

Partial Air Lift Designs --

Partial air lift designs are those systems where hypolimnetic water is aerated and circulated by an air injection system, but where the air/water mixture does not upwell to the lake's surface. Instead, the water and air separate well below the lake's surface. The water is returned to the hypolimnion and the air is wasted to the atmosphere. Two partial air lift designs have been described.

The partial air lift designs appear to be much less efficient than the full air lift designs. Although the partial air lifts have greater effluent oxygen concentrations, they aerate less water volume and the total oxygen dissolved is less than full air lift designs. Most of the energy used

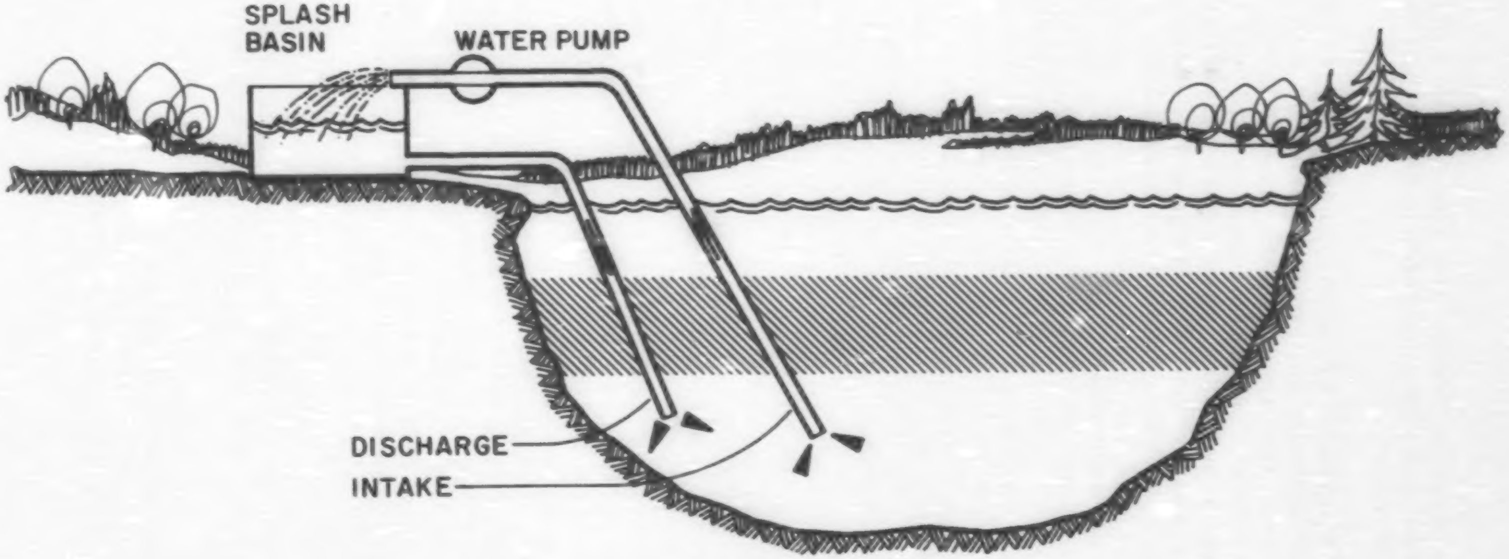
SPLASH
BASIN
WATER PUMP
DISCHARGE
INTAKE

Figure B-1. Mechanical aeration system of hypolimnion aeration from Lake Bret, Switzerland (Mercier and Perret, 1949; Mercier and Gay, 1954; Mercier, 1955).

to compress the air is "lost" in the waste air discharge line, and the air does not expand greatly while it is in contact with the water.

The Limno System[1] of hypolimnetic aeration is the most widespread hypolimnetic aerator in present use (Figure B-2). Five Limno Systems are in European use (Bjork, 1974), while one system is in North American use (Fast, et al., 1975a). The original Limno aerators were constructed of steel, but now the design is standardized and they are constructed of molded fiberglass. Each chamber measures only 15 feet high by 8 feet in diameter (28 feet diameter overall with outlet arms). Compressed air is released from a diffuser at the bottom of the aerator and rises within the aeration chamber. Upon reaching the top of the chamber, the air and water separate. The waste air is vented to the atmosphere through a small diameter pipe and the water reverses its flow and returns to the hypolimnion through six outlet pipes. A valve on the wastes gas discharge pipe maintains pressure on the waste gas and thus creates a gas "pocket" at the top of the aeration chamber. This prevents the escape of water through the waste gas discharge pipe. A shore based air compressor can supply air to one or more submerged aeration chambers. One air compressor (280 SCFM, 40 H.P., single stage) provided air to two Limno aerators at Lake Waccabuc, New York (Fast, 1973b). This system had an oxygen absorption efficiency of 1.2 lbs O_2/kw-hr. The water to air ratio was 3.8:1 and only 10.6% of the injected oxygen was absorbed. A substantial increase in dissolved nitrogen gas occurred in the hypolimnion, and after 80 days of continuous aeration the hypolimnion was 150% saturated with N_2 relative to surface pressures (Fast, et al., 1975a). Hypolimnetic phosphorus concentrations were apparently not greatly reduced by aeration, even though hypolimnetic oxygen concentrations were typically greater than 2 mg/ℓ during the second summer of aeration (Fast, 1975). Hypolimnetic ammonia concentrations increased greatly during aeration, and nitrification apparently was not greatly accelerated by the increased oxygen concentrations (Confer, et al., 1974b) There was no apparent effect of the aeration on algal or zooplankton densities (Fast, 1975; Confer, et al., 1974a). Rainbow trout (Salmo gairdneri Richardson) survived in Lake Waccabuc with hypolimnetic aeration, whereas they did not prior to aeration.

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(1) Registered Trademark of Atlas Copco, AB. A U.S. patent was allegedly applied for circa 1972, on this system, but its present status is unknown.

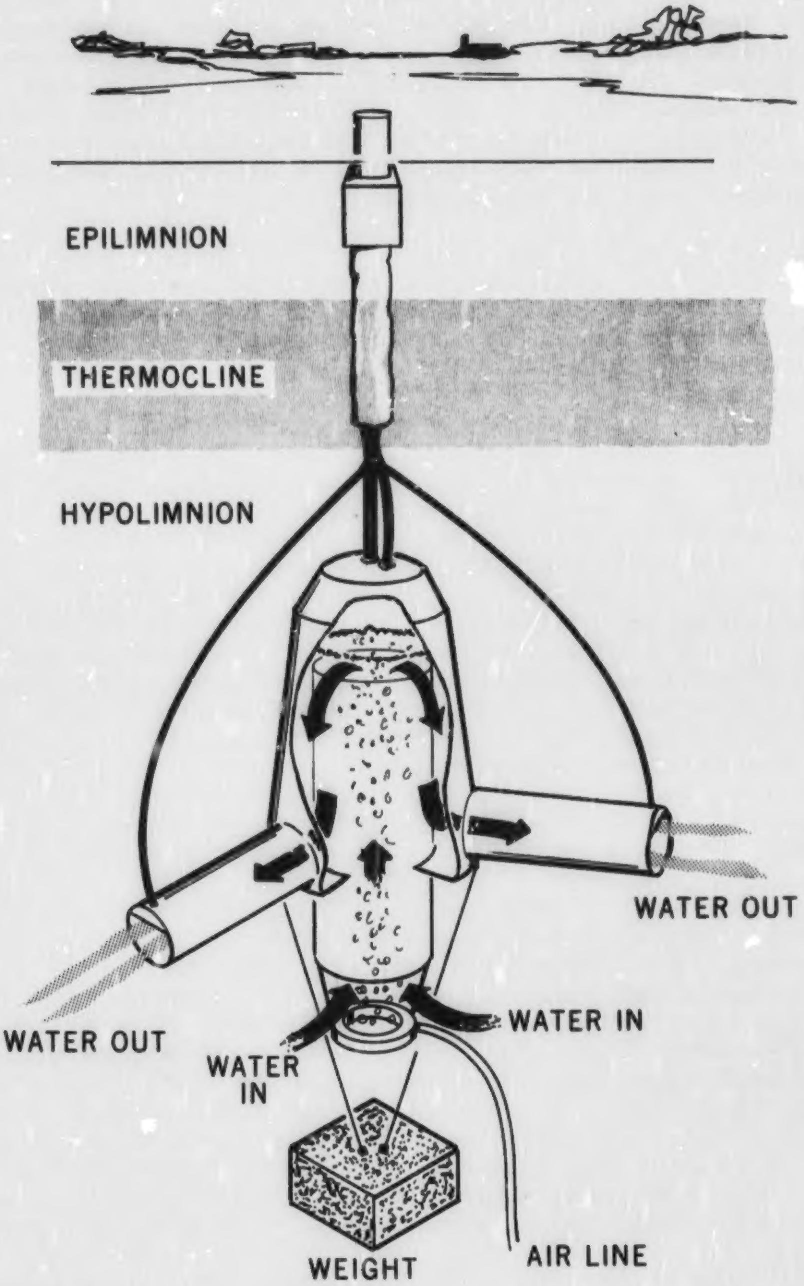
EPILIMNION
THERMOCLINE
HYPOLIMNION
WATER OUT
WATER IN
WATER OUT
WATER IN
WEIGHT
AIR LINE

Figure B-2. Exposed view of Limno hypolimnetic aerator. This is a partial air lift design since hypolimnetic waters are upwelled only a short distance by air injection (Fast, Dorr and Rosen, 1975a).

Speece, et al., (1974) proposed another partial air lift system (Figure B-3), but this system has not been tested. It is essentially the same design as the Limno except that the waste gas discharge pipe does not have a valve, and a gas pocket may not be created. Consequently, gas and water may be pumped through the gas discharge line. Provisions may have to be made to return this water to the hypolimnion. Otherwise, substantial quantities of hypolimnetic water may be pumped into the epilimnion.

Full Air Lift Designs --

Full air lift designs are those systems where compressed air is injected near the bottom of the aerator and the air/water mixture rises to near the lake's surface. The air then separates from the mixture and the water is returned to the hypolimnion.

Fast (1971) described one of the first full air lift, hypolimnetic aerators (Figure B-4). This aerator consisted of concentric upwelling and downwelling pipes. Air was released within the center pipe and rose to the lake's surface. The efficiency of this system was greatly reduced because of the restricted outflow, but proposed modifications to this system should greatly increase its efficiency and reduce its capital cost (Fast, et al., 1975c). With this system in Hemlock Lake, Michigan, hypolimnetic oxygen concentrations were increased from 0 to over 8 mg/l and rainbow trout distributed throughout the hypolimnion (Fast, 1973a). Phytoplankton and zooplankton densities varied greatly during aeration. This was due in part to leaks in the aerator which allowed nutrient rich waters to mix with the epilimnion and thus promote algal growth (Fast, et al., 1973).

Bernhardt (1974) described another aerator which incorporates individual upwelling and downwelling pipes, separated by a horizontal degassing chamber (Figure B-5).(2) This aerator was used in Wahnbach Reservoir, West Germany, and has one of the greatest efficiencies yet reported. Its efficiency was 2.5 lbs O_2/kw-hr, with absorption of 50% of the injected oxygen. Bernhardt injected 247 SCFM of air at the 120 foot depth in a 5.5 foot diameter upwelling pipe and observed a water:air ratio of 31:1. The diameter of the downwelling pipe was 9.8 feet. This system greatly reduced the dissolution of iron, manganese and phosphorus from the sediments while at the same time maintained cold aerated waters in the hypolimnion.

Two similar full air lift hypolimnetic aerators were used to aerate lakes Tullingesjön and Järlasjön, Sweden

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(2) A U.S. patent was issued in 1974 (Hirshon, 1974) which appears to embody many of the features of the Bernhardt design. However, this patent does not reference some of the more pertinent literature, and it may not withstand a legal test of its claims.

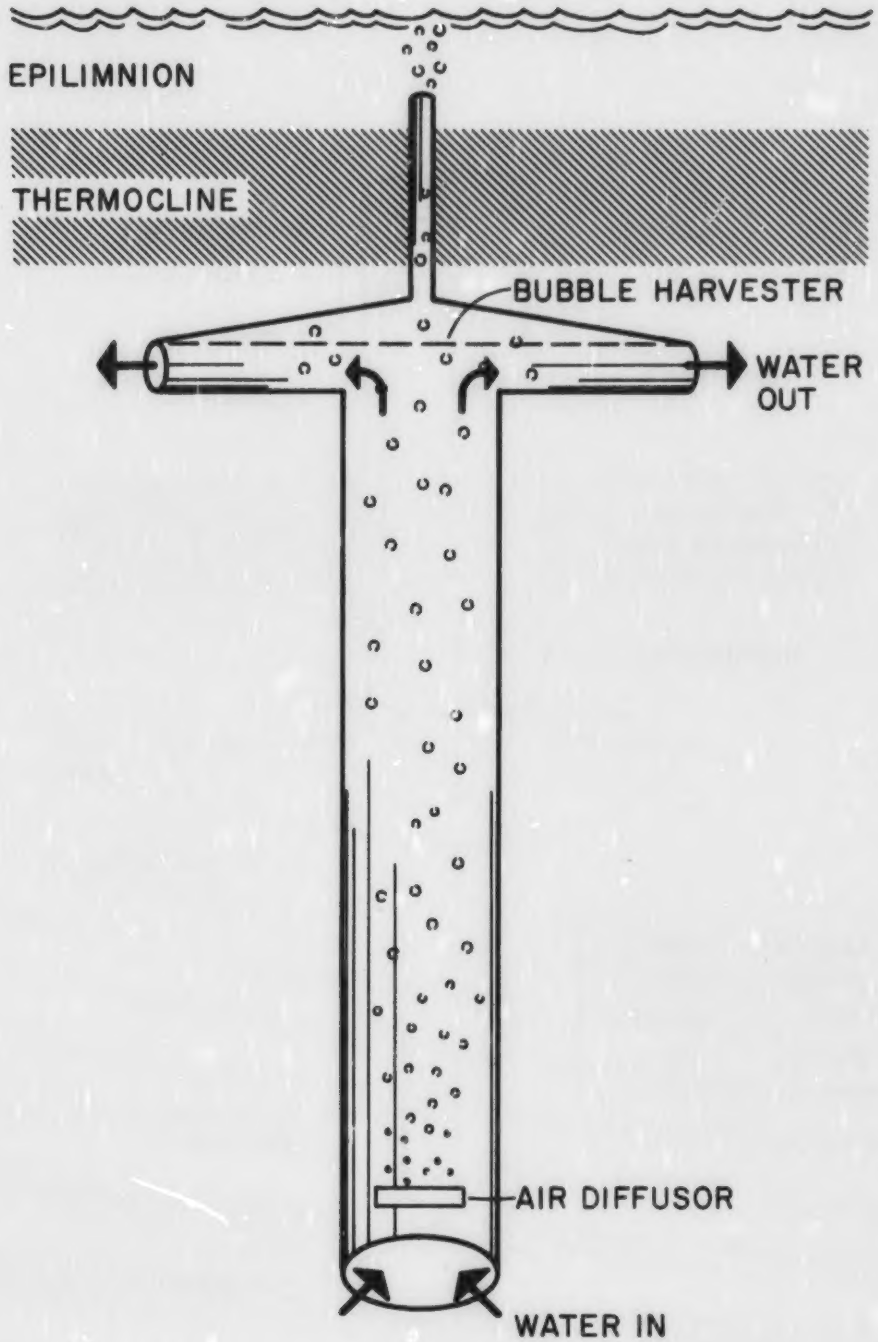
EPILIMNION
THERMOCLINE
BUBBLE HARVESTER
WATER OUT
AIR DIFFUSOR
WATER IN

Figure B-3. A proposed partial air lift system of hypolimnetic aeration (Speece, et al., 1974)

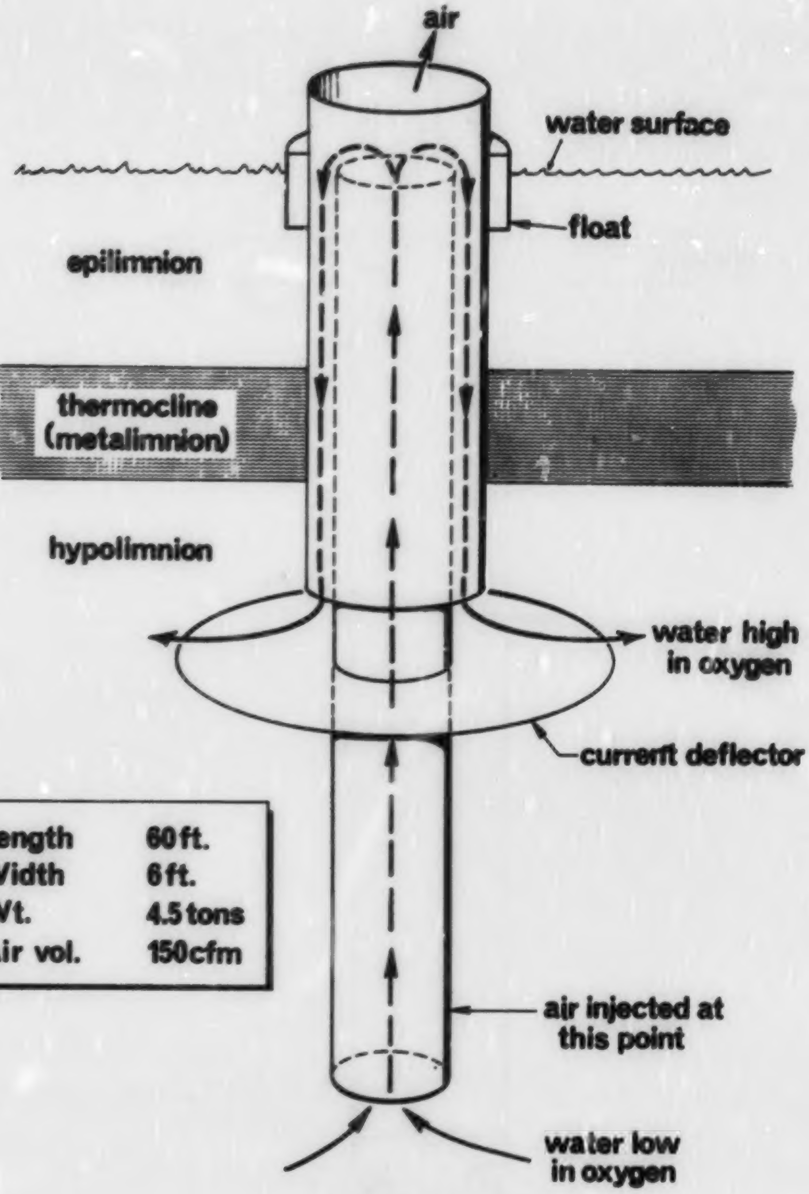
air
water surface
float
epilimnion
thermocline
(metalimnion)
hypolimnion
water high in oxygen
current deflector
Length 60 ft.
Width 6 ft.
Wt. 4.5 tons
Air vol. 150 cfm
air injected at this point
water low in oxygen

Figure B-4. A full air lift, hypolimnetic aeration used in Hemlock Lake, Michigan (Fast, 1971). This is a full air lift design since water is upwelled to the surface before it returns to the hypolimnion.

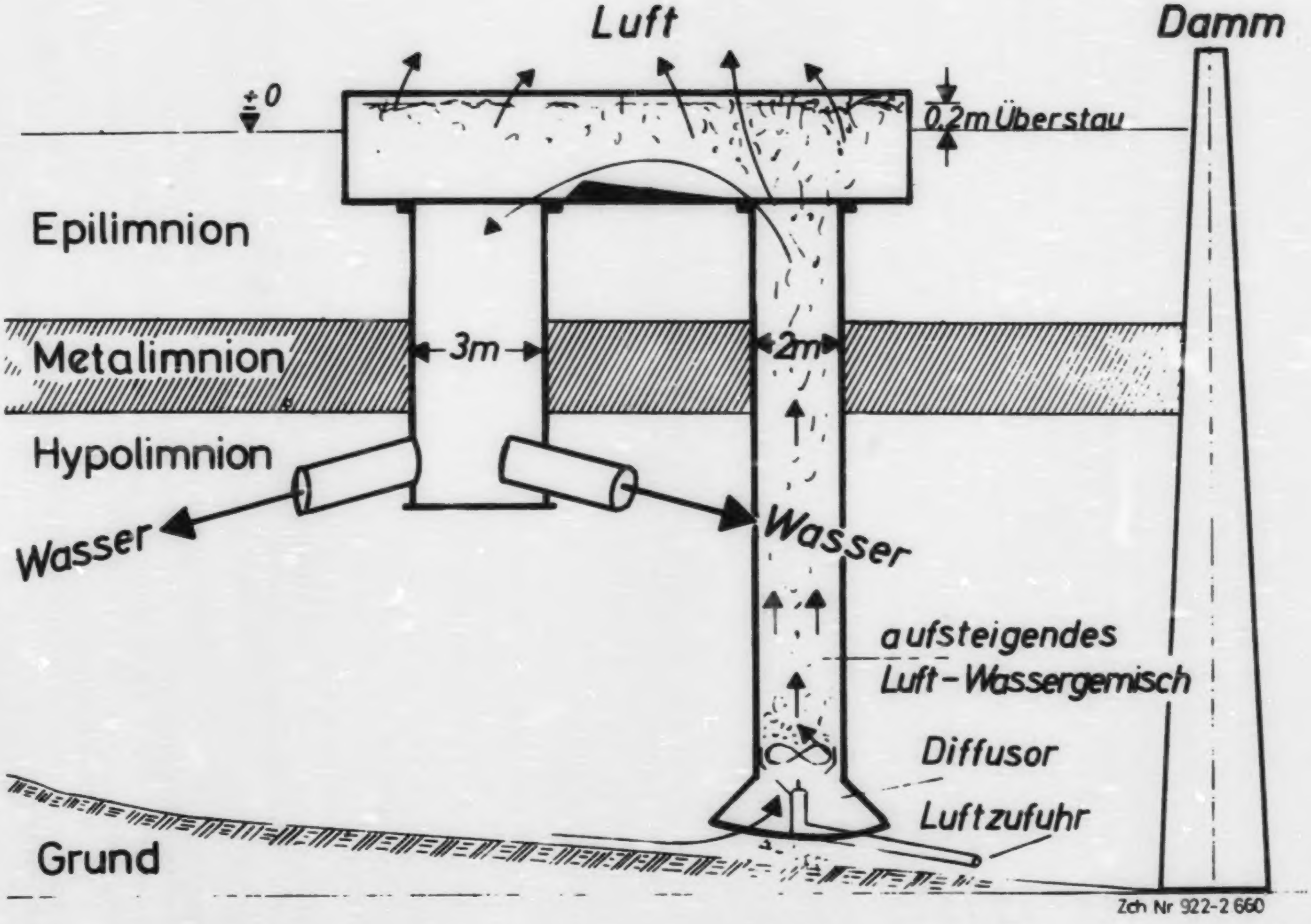
Luft
Damm
±0
0,2m Überstau
Epilimnion
Metalimnion
3m
2m
Hypolimnion
Wasser
Wasser
aufsteigendes
Luft-Wassergemisch
Diffusor
Luftzufuhr
Grund
Zch Nr 922-2 660

Figure B-5. A full air lift, hypolimnetic aerator used in Wahnbach Reservoir, West Germany (Bernhardt, 1974).

(Bengtsson, et al., 1972). These systems were nearly identical except for the placement of the upwelling pipe, and the number of outlet pipes.

The Lake Tulligesjön aerator had one 1.3 foot diameter upwelling tube which discharged horizontally into the box-like degassing chamber (Figure B-6). It had four 1.6 foot diameter outlet pipes which distributed the aerated water throughout the hypolimnion (Figure B-7). About 530 SCFM of compressed air were injected. Hypolimnetic oxygen concentrations were not increased above 0.0 mg/ even though Lake Tullingesjön was aerated for more than 2-1/2 months. Hypolimnetic ammonia concentrations were decreased slightly during aeration, but hypolimnetic nitrate concentrations were not significantly changed by aeration.

The Lake Järlasjön aerator differed from the Lake Tullingesjön aerator primarily in the placement of the upwelling tube and the number of outlet tubes. The Lake Järlasjon aerator had one 2 foot diameter upwelling pipe which extended through the bottom of the degassing chamber and discharged "concentrically" into the chamber (Figure B-8). Ten 1.6 foot diameter outlet pipes distributed the aerated water back into the hypolimnion (Figure B-9). About 789 SCFM of air were injected into the upwelling tube. Lake Järlasjön was aerated one summer. Hypolimnetic ammonia was greatly reduced and nitrification was apparently increased by aeration. Nitrate concentrations were more than 1.4 mg/ℓ with aeration and less than 0.1 mg/ℓ without, whereas ammonia concentrations were correspondingly less than 0.1 mg/ℓ with aeration and 1.6 mg/ℓ without aeration. Phosphorus was slightly reduced during aeration.

The efficiencies of the Lakes Tullingesjön and Järlasjön aeration systems were greatly reduced by the very large air injection rate and small diameter upwelling pipe. These conditions for the Swedish aerators reduced oxygen absorption efficiencies and water volumes pumped per unit volume air injected. The upwelling plume from the Lake Järlasjön aerator shot about 6 feet above the lake's surface.

Smith, et al., (1975) described a design similar to Bernhardt's (Figure B-5) (Figure B-10). It is constructed of inexpensive materials such as plywood, has flexible outlet tubes and styrofoam flotation. The upwelling pipe contained a patented helical insert which was supposed to increase oxygen absorption. However, Smith, et al. reported that it may have reduced absorption since the bubbles tended to be channeled up the center of the helix (Knauer, pers. comm., 1974; Smith, et al., 1975).

Downflow Air Injection --

Speece (1970) and Speece, et al. (1974) have proposed two hypolimnetic aeration devices which use a mechanical water

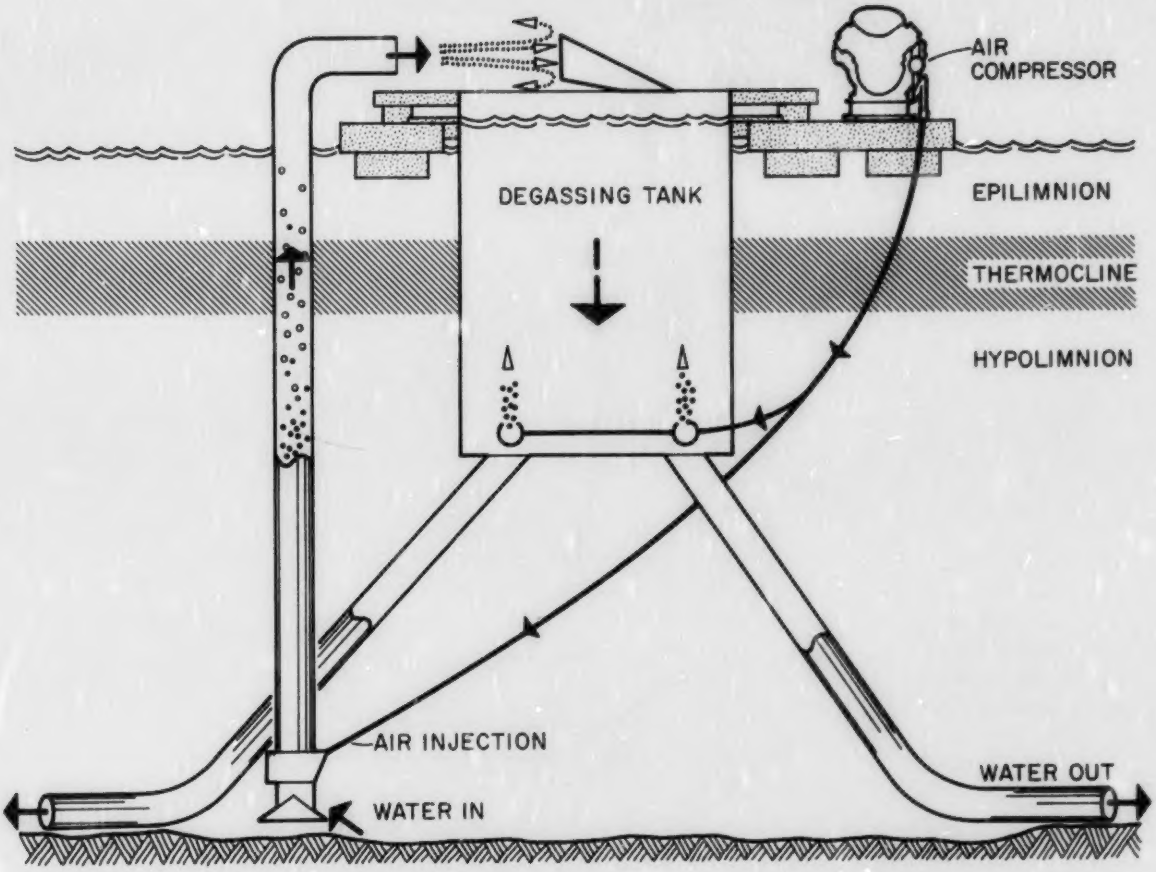
AIR
COMPRESSOR
DEGASSING TANK
EPILIMNION
THERMOCLINE
HYPOLIMNION
AIR INJECTION
WATER OUT
WATER IN

Figure B-6. A full air lift, hypolimnetic aerator used in Lake Tullingesjön, Sweden (Bengtsson, et al., 1972).

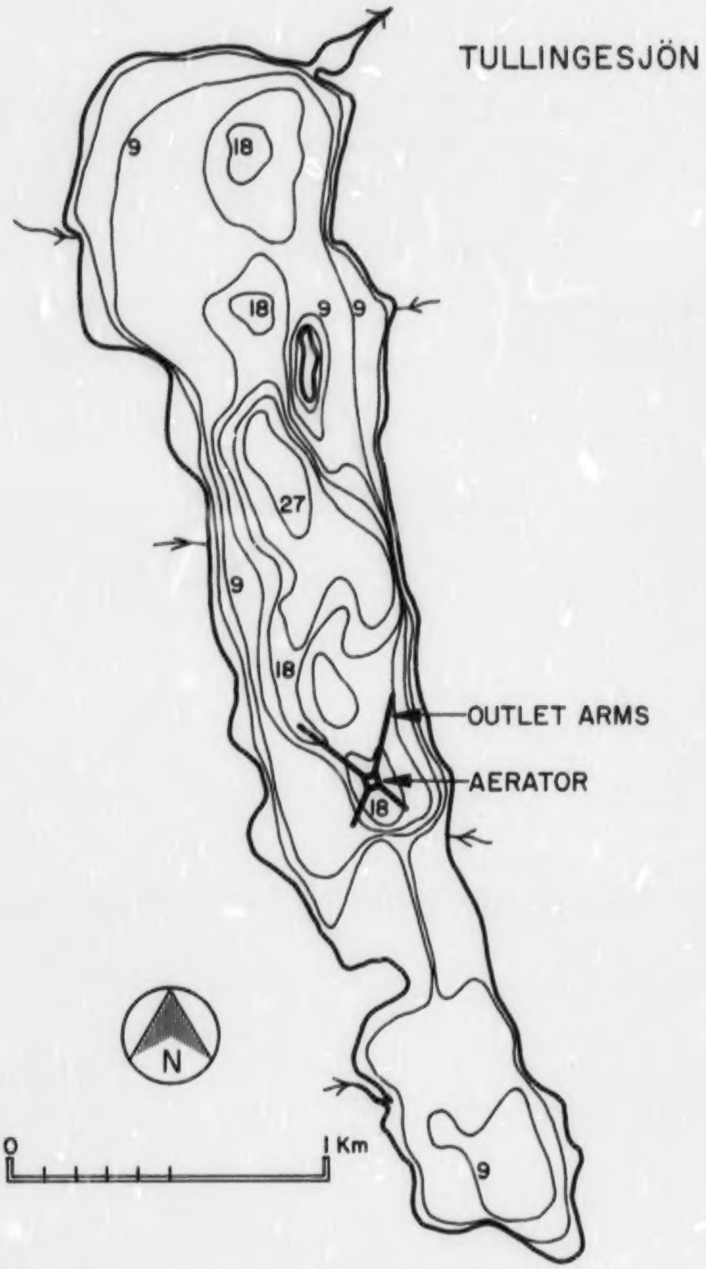
TULLINGESJÖN
9
18
18
9
9
27
9
18
OUTLET ARMS
AERATOR
18
N
0
1 Km
9

Figure B-7. Plan view of Lake Tullingesjön, Sweden, showing the hypolimnetic aerator with four outlet pipes (Bengtsson, et al., 1972).

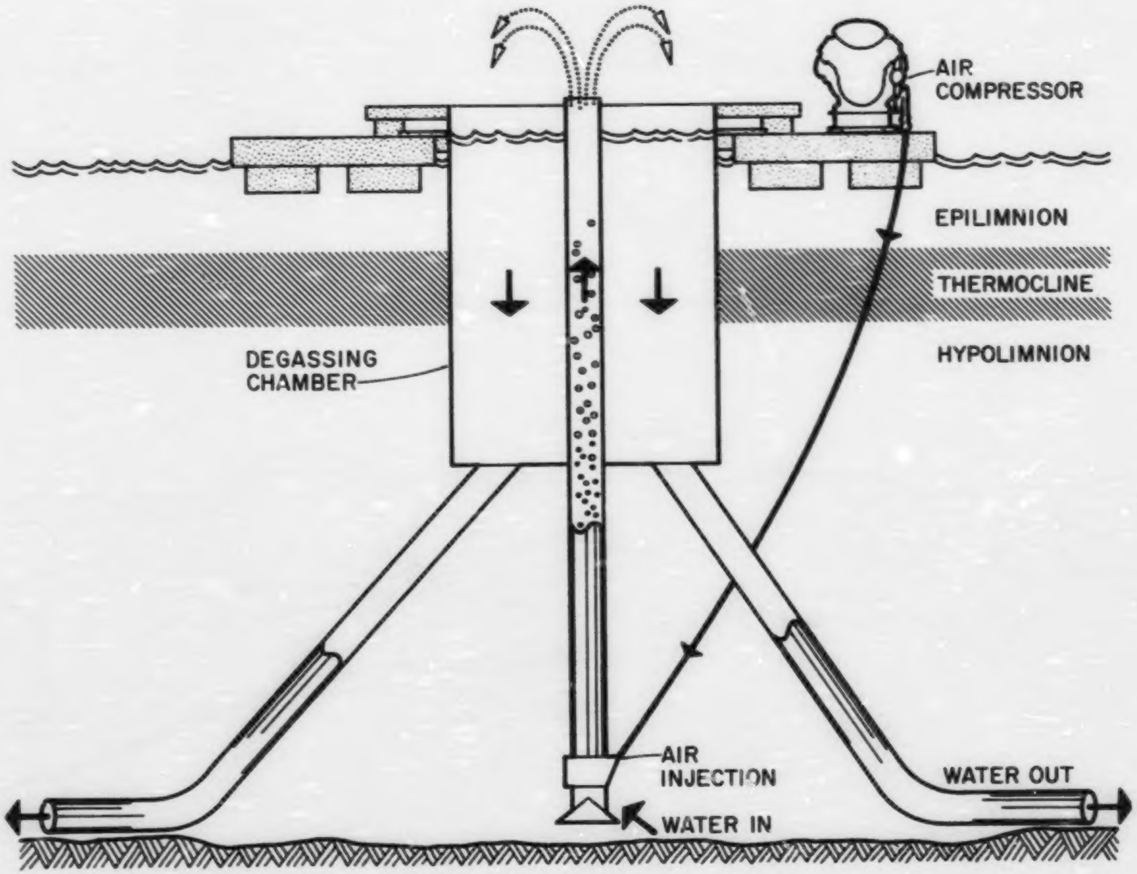
AIR COMPRESSOR
EPILIMNION
THERMOCLINE
HYPOLIMNION
DEGASSING CHAMBER
AIR INJECTION
WATER IN
WATER OUT

Figure B-8. Full air lift, hypolimnetic aerator used at Lake Järlasjön, Sweden (Bengtsson, _et al_., 1972).

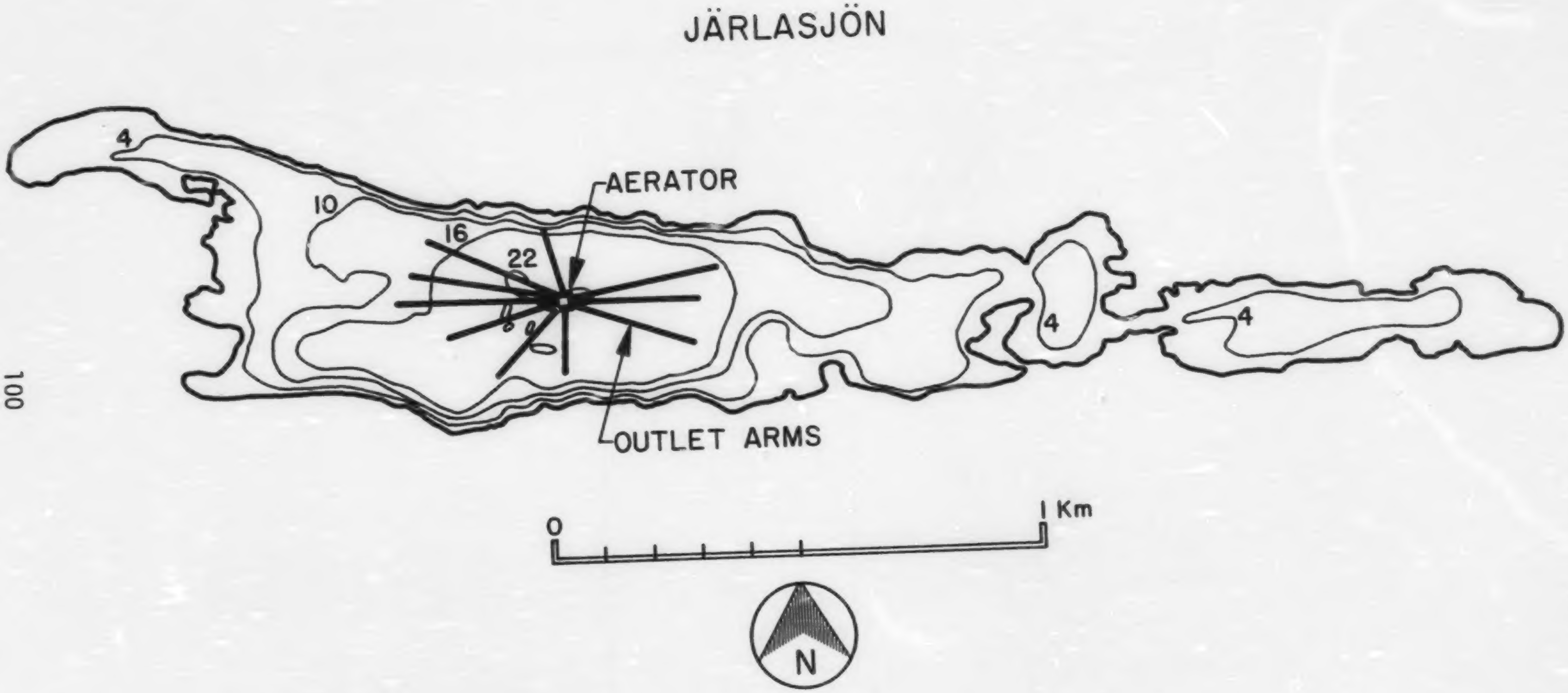
JÄRLASJÖN
AERATOR
OUTLET ARMS
4
10
16
22
4
4
0
1 Km
N

Figure B-9. Plan view of Lake Järlasjön, Sweden showing the hypolimnetic aerator and ten outlet pipes (Bengtsson, *et al.*, 1972)

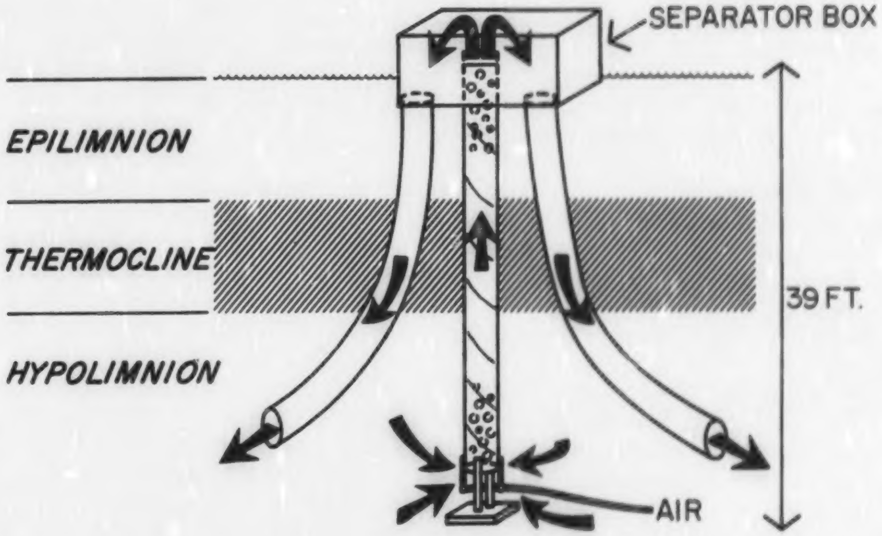
SEPARATOR BOX
EPILIMNION
THERMOCLINE
HYPOLIMNION
39 FT.
AIR

Figure B-10. Full air lift, hypolimnetic aerator used in Mirror and Larson Lakes, Wisconsin, by Smith, Knauer and Wirth, (1975).

pump to force a flow of water down a vertical pipe (Figures B-11, B-12). Air is injected below the pump, but the downward velocity of the water is greater than the rise velocity of the bubble. Consequently, the air bubbles are swept downward and separation of the air/water mixture takes place in the hypolimnion. The advantages of this technique are that the air/water contact time is increased for a given length pipe, the bubbles are exposed to a continuously increasing oxygen saturation gradient, and a low pressure air compressor is needed. These factors tend to increase the percentage of oxygen absorbed from the air. However, the large water velocity required would also complicate air/water separation, and additional energy is required to mechanically pump the water. Furthermore, dissolved nitrogen gas concentrations will be greatly increased by these systems, and unacceptable N_2 concentrations may occur.

Speece's first system incorporates both the downflow air injection and air lift pump features (Figure B-11) (Speece, 1971). This should increase its efficiency since some of the energy required to compress the air is recovered as the bubbles rise in the upwelling tube.

Speece's later version does not make use of the potential energy of the waste gases (Figure B-12) (Speece, et al., 1974). Instead, the waste gases are vented to shallow water, and hypolimnetic water is hopefully confined to the hypolimnion. In practice, hypolimnetic water may be pumped through the waste gas vent unless sufficient pressure is maintained therein.

Other Air Lift Designs --

One of the first successful hypolimnetic aerators was the "standpipe" aerator described by Bernhardt for Wahnbach Reservoir, West Germany (Figure B-13) (Bernhardt, 1967). Superficially, this aerator looks like a full air lift design. However, most of the water does not rise to the top of the aerator. Instead, it separates from the air at the level of the outlet arms and returns to the hypolimnion. In essence, it is nearly identical in concept to the partial air lift design shown in Figure B-4.

Bernhardt reportedly injected 142 SCFM of air into the aerator and observed an oxygen absorption of 50%, or an efficiency of 2.1 lbs O_2/kw-hr. This is only slightly less efficient than his newer design (2.5 lbs O_2/hr) which has since replaced this aerator at Wahnbach Reservoir (Bernhardt, 1967). The original aerator reduced the rate of oxygen depletion during thermal stratification, which in turn reduced the manganese and phosphorus concentrations in the hypolimnion.

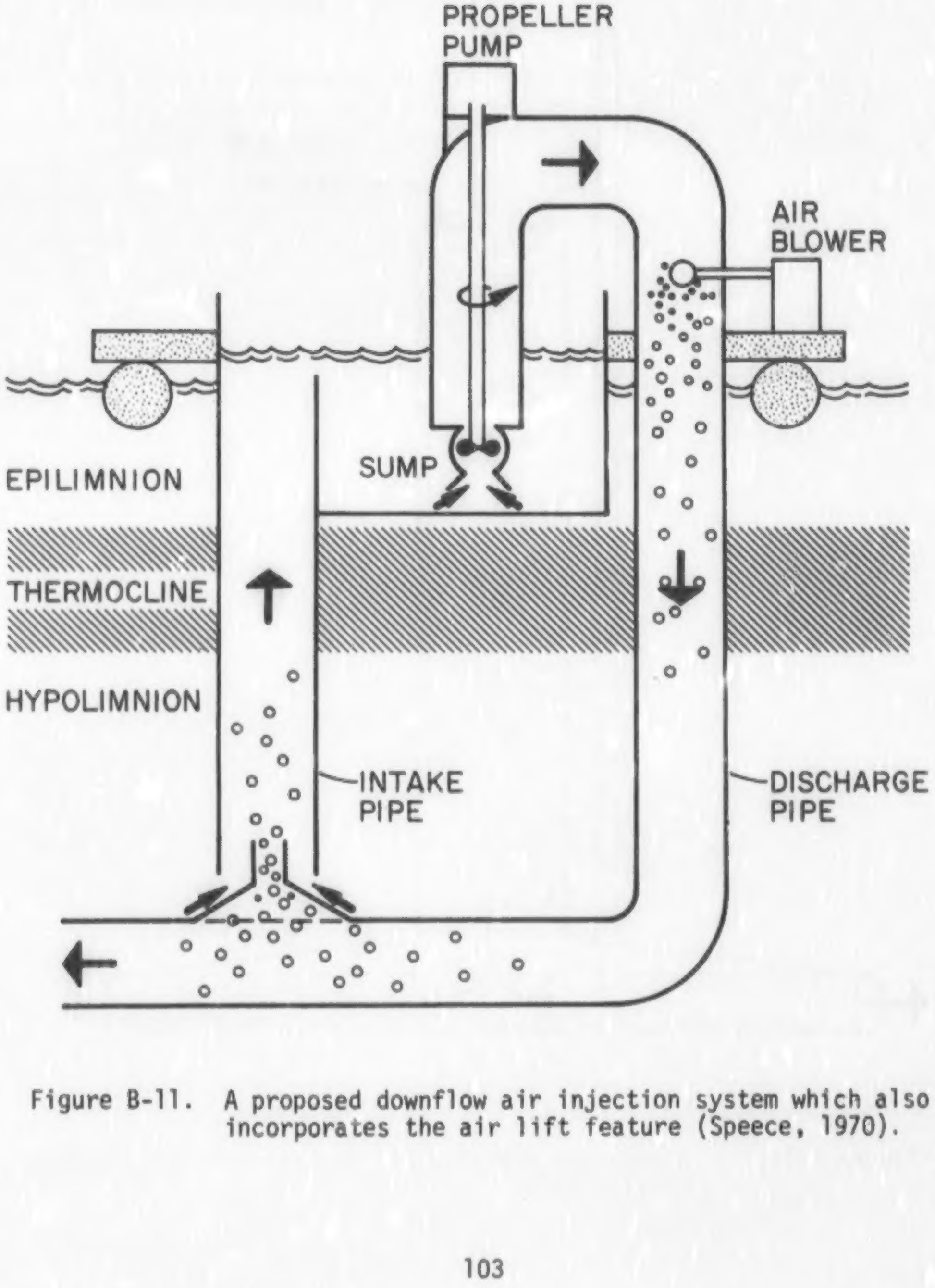
PROPELLER PUMP
AIR BLOWER
EPILIMNION
SUMP
THERMOCLINE
HYPOLIMNION
INTAKE PIPE
DISCHARGE PIPE

Figure B-11. A proposed downflow air injection system which also incorporates the air lift feature (Speece, 1970).

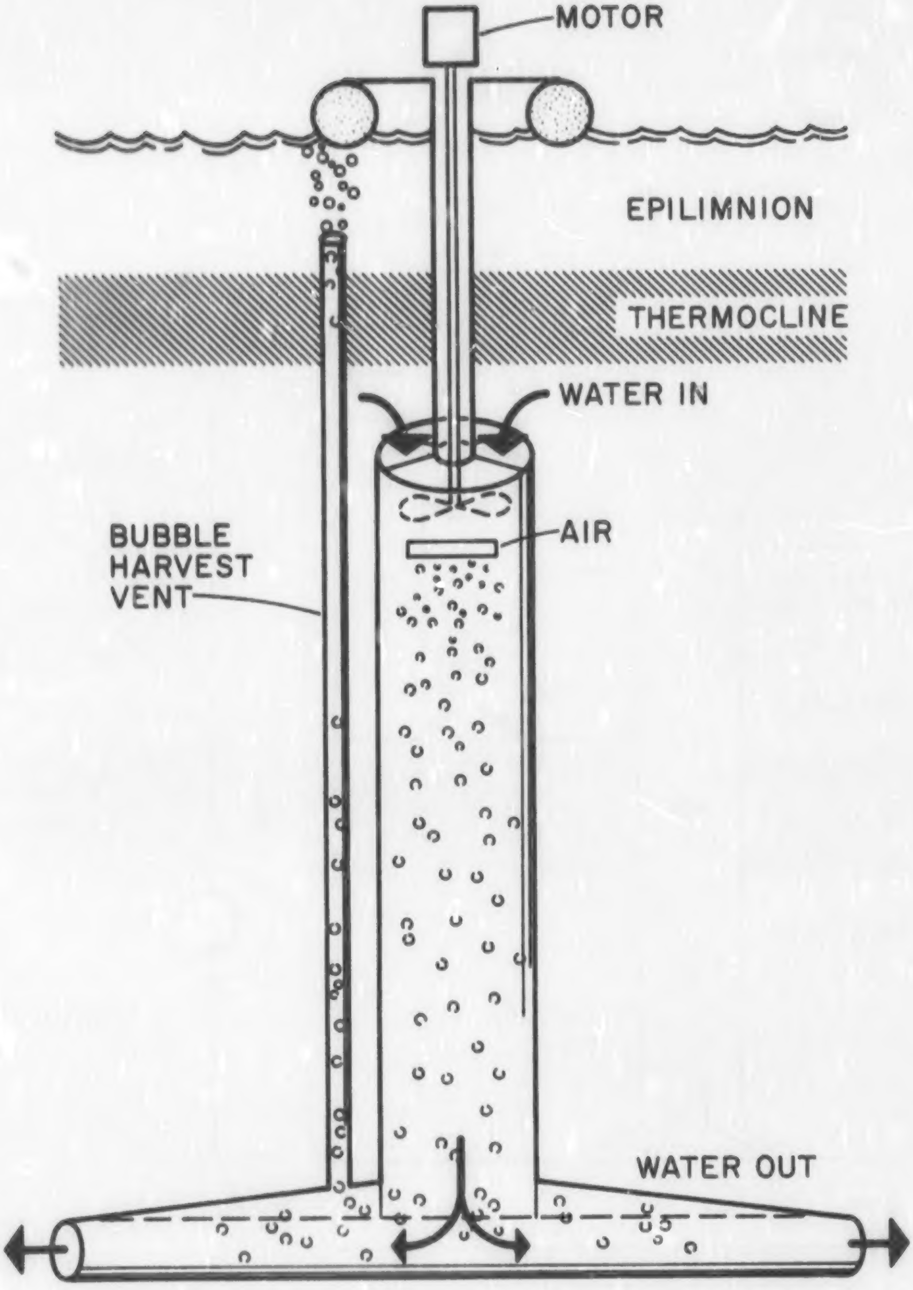
MOTOR
EPILIMNION
THERMOCLINE
WATER IN
AIR
BUBBLE HARVEST VENT
WATER OUT

Figure B-12. A proposed downflow air injection system (Speece, et al., 1974).

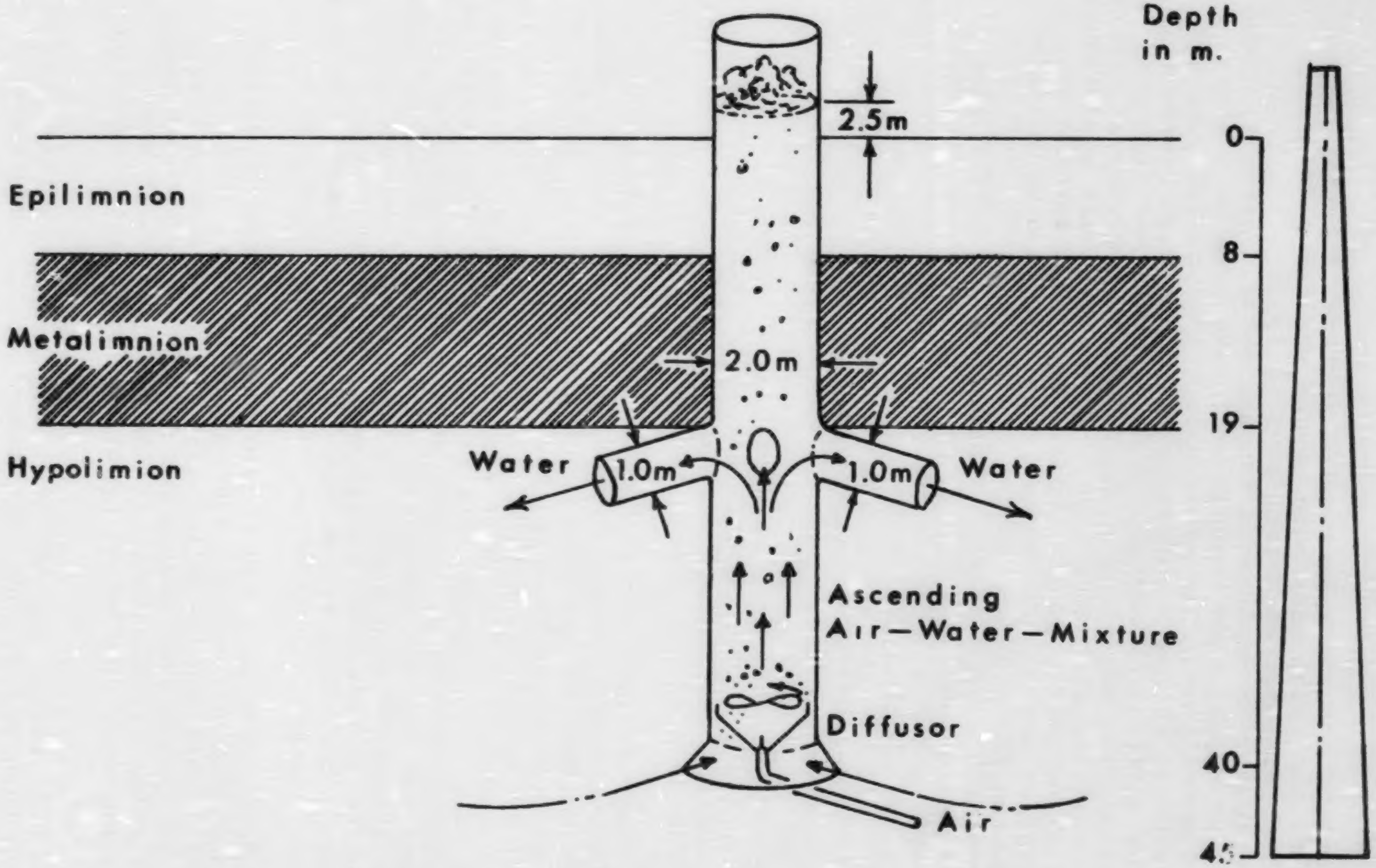
Depth
in m.
2.5m
0
8
19
40
45
Epilimnion
Metalimnion
Hypolimion
2.0m
Water
1.0m
1.0m
Water
Ascending
Air—Water—Mixture
Diffusor
Air

Figure B-13 "Stand-pipe" hypolimnetic aerator used at Wahnbach Reservoir, West Germany (Bernhardt, 1967).

Oxygen Injection Systems

One of the first successful systems of hypolimnetic oxygenation which uses pure oxygen was the side stream pumping (SSP) system (Fast, et al., 1975b).[3] It is conceptually uncomplicated (Figure B-14). Water is drawn from the hypolimnion through an intake pipe by a shore based water pump. The water passes through the pump and is returned to the hypolimnion through a high pressure discharge line. Since nearly pure oxygen and high pressures are used, the oxygen is almost completely dissolved before it leaves the discharge pipe. This system was successfully used at Ottoville Quarry, Ohio, where hypolimnetic oxygen concentrations were increased from zero to 8 mg/ℓ during 1973, and to 21.5 mg/ℓ during 1974 (Overholtz, 1975). Hypolimnetic temperatures increased 5°C and 9°C during 1973 and 1974 respectively due to the induced water currents. The system had a 5 H.P. water pump and maximum oxygen input capacity of about 50 lbs/day (Fast, 1973b; Matsch, 1973). This indicates an oxygen absorption efficiency of 1.5 lbs O_2/kw-hr, assuming an energy consumption of 800 kw-hr/ton of liquid oxygen (Fast, et al., 1975c); Lyon, personal comm., 1975). As a consequence of SSP oxygenation, rainbow trout survived yearlong at Ottoville Quarry (Annon., 1973; Overholtz, 1975). This greatly increased recreational use of the quarry, but special tenchinques were required to stock the fish during the summer (Overholtz, 1975).

A second SSP test at Attica Reservoir, Attica, New York, was unsuccessful (Fast, Overholtz and Tubb, M.S.; Haines, 1974; Matsch, 1973). The SSP system at Attica was larger and the reservoir was much shallower than at Ottoville. Although only 1.3% of the hypolimnetic water volume during 1973, and 0.7% during 1974 was pumped through the system each day, the reservoir was rapidly destratified each year. In Ottoville Quarry, 1.3% of the hypolimnetic volume was pumped per day but thermal stratification was maintained. This indicated that a much reduced water flow rate is required to maintain thermal stratification in shallow lakes. The Attica system was designed to dissolve 60 lbs of oxygen/day, for an efficiency of 0.17 lbs O_2/kw-hr.

Speece has proposed a deep oxygen bubble injection method of hypolimnetic oxygenation (Speece, 1971, 1973, 1975). This technique involves the injection of high purity oxygen from coarse bubble diffusers at some depth within the hypolimnion. If the hypolimnion is deep enough (e.g., 60 feet of hypolimnetic height), then most

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[3] A U.S. patent was allegedly applied for during 1974 on this system, but its present status is unknown.

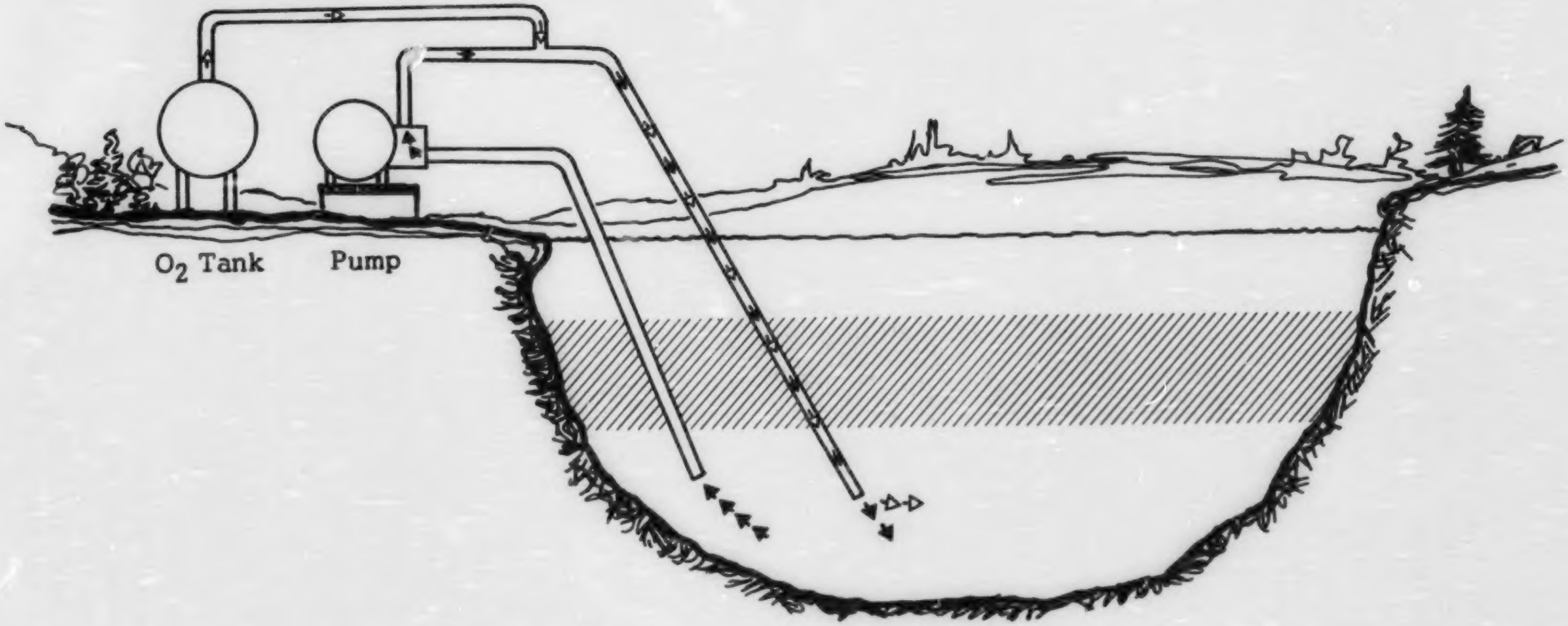


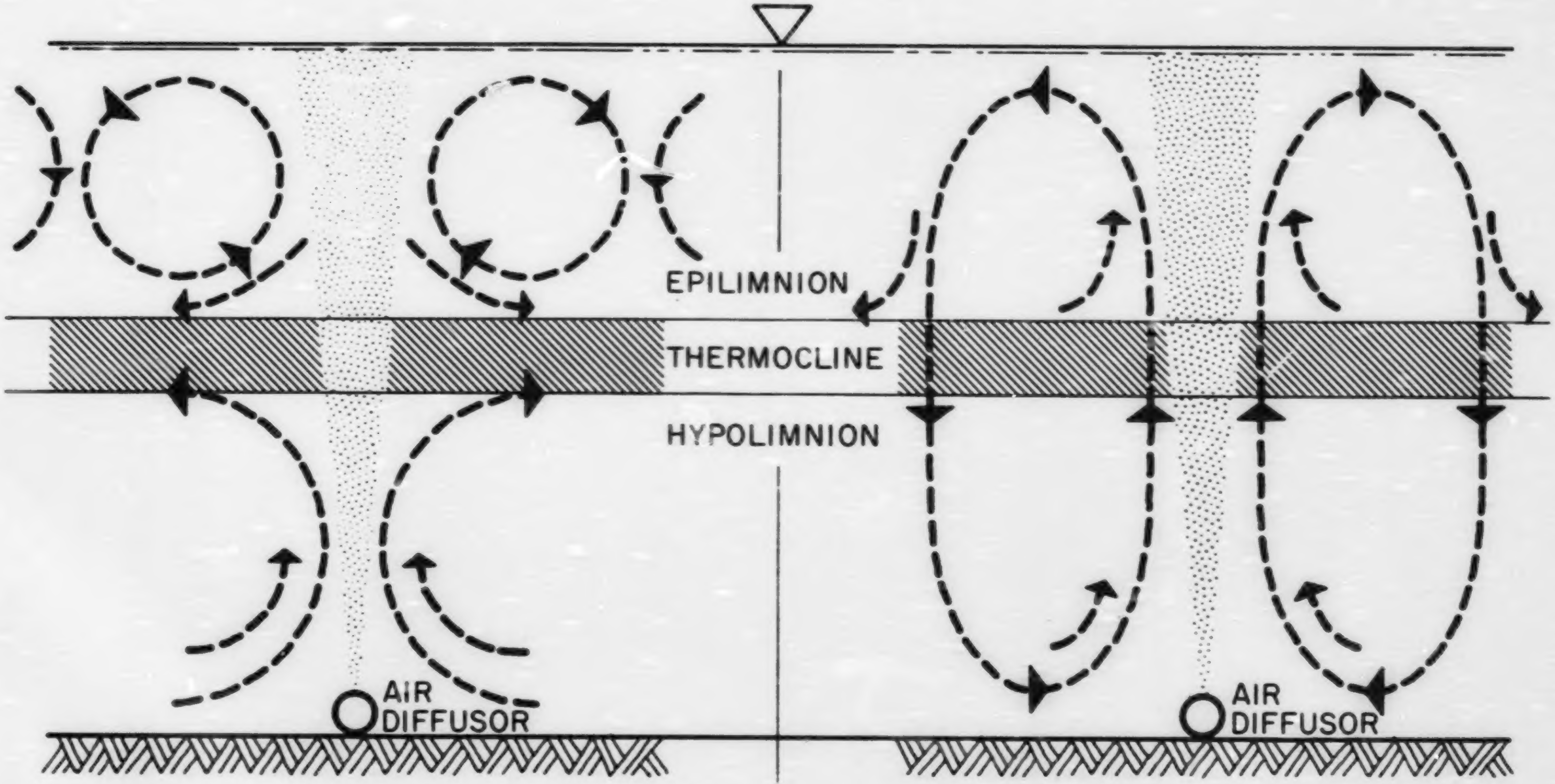
Figure B-14. Schematic view of the hypolimnion oxygenation system used at Ottoville Quarry, Ohio and Attica Reservoir, New York (Fast, Overholtz and Tubb, 1975b). The cross-hatched area represents the thermocline.

of the bubble will be dissolved before it reaches the thermocline. If the gas volume is small, then according to Speece, the bubbles will "uncouple" through the thermocline to the lake's surface while the oxygenated hypolimnetic water will remain in the hypolimnion (Figure B-15 and B-16). The oxygenated hypolimnetic water will partially mix the warmer thermocline water and form a "sandwich layer" at the base of the thermocline. The sandwich layer will spread out from the plume area. If the rate of gas input is too great, then the upwelled hypolimnetic water may penetrate the thermocline and excess mixing with shallow water may occur.

If in fact uncoupling occurs and oxygen can be economically and reliably produced, then this technique may have practical application, especially for meeting tailwater oxygen-temperature discharge requirements. Some form of pure oxygen injection may be required in these situations since air injection can in some cases cause unacceptable dissolved nitrogen gas concentrations. The full extent of this potential problem is still undocumented. Even with pure oxygen injection, nitrogen gas can become supersaturated due to hypolimnetic warming (Fast, Overholtz and Tubb, M.S.).

Deep oxygen bubble injection may not be feasible if uncoupling is not complete, and/or if oxygenated water does not mix throughout the hypolimnion. This situation could lead to a sandwich layer with high oxygen content, and an oxygen depleted zone near the lake bottom. On-site generation of oxygen is feasible in some large volume situations, especially if the oxygen can be continuously injected without liquification. Importation and/or storage of liquid oxygen can be prohibitively expensive and unreliable. As far as we know, deep oxygen bubble injection has not been used full scale to oxygenate a lake's hypolimnion other than for discharge purposes.

Speece also proposed the use of downflow bubble-contact aerator (DBCA) for hypolimnetic oxygenation (Speece, 1970, 1971, 1973; Speece et al., 1974). This cone shaped device could be suspended within the hypolimnion (Figure B-17). A pump forces water downward and pure oxygen is diffused below the pump. Bubble contact time is lengthened by this device as with the downflow air injection. The high water velocity in the throat (8 ± 2 ft/sec) prevents gas bubbles from escaping through the top of the funnel. Instead, the bubbles are forced under the lower rim after about 15 seconds contact time. By then, much of the oxygen has diffused out of the bubble and into the water, while nitrogen gas has diffused into the bubble. The waste bubbles then rise to the surface. This waste stream will entrain water


EPILIMNION
THERMOCLINE
HYPOLIMNION
AIR DIFFUSOR
AIR DIFFUSOR

(A) COMPLETE UNCOUPLING BETWEEN PLUME WATER AND GAS BUBBLES

(B) PARTIAL OR NON-UNCOUPLING BETWEEN PLUME WATER AND GAS BUBBLES

Figure B-15. Proposed modes of bubble and water plume interactions during deep oxygen bubble injection (Speece, 1975b).

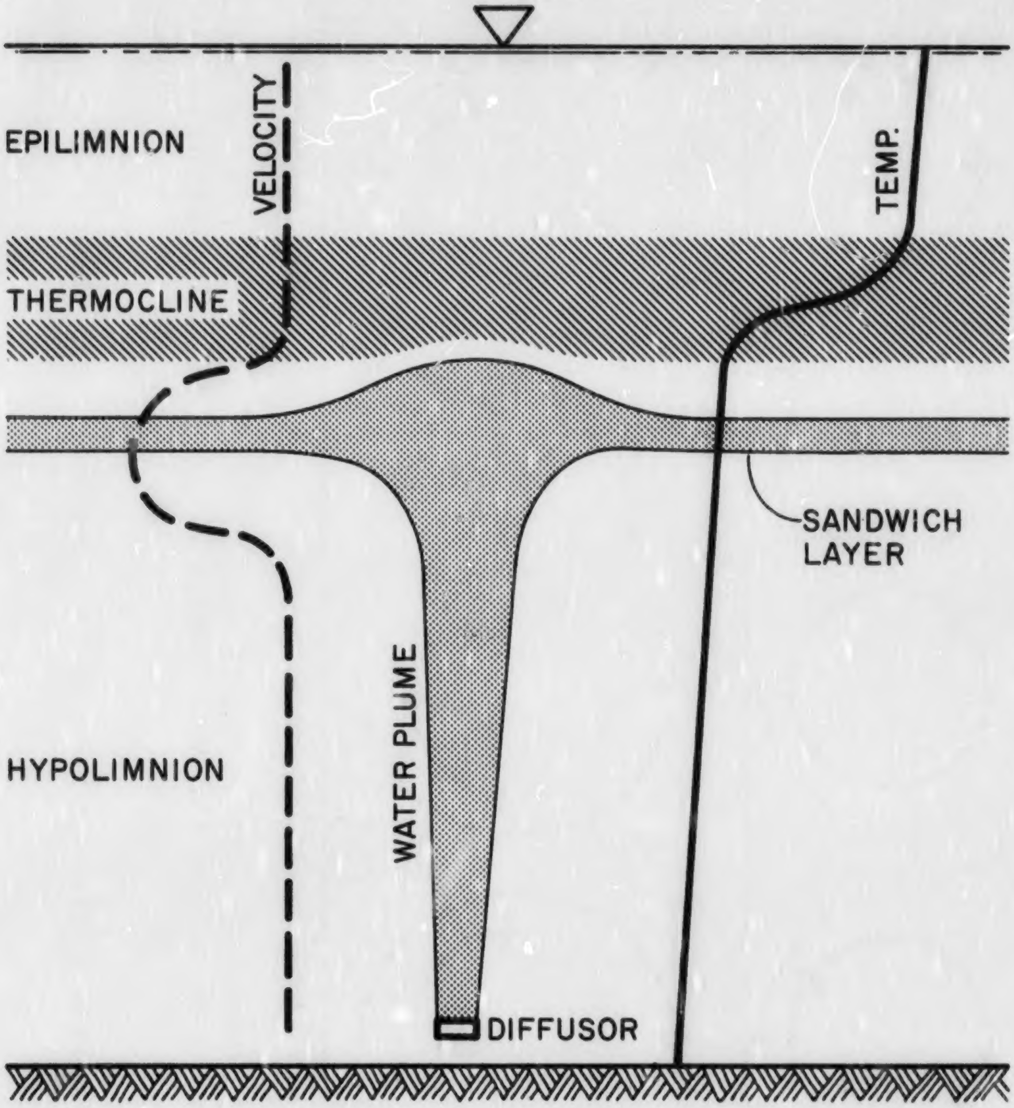

EPILIMNION
VELOCITY
TEMP.
THERMOCLINE
SANDWICH LAYER
WATER PLUME
HYPOLIMNION
DIFFUSOR

Figure B-16. Proposed oxygenated water plume behavior during deep oxygen bubble injections (Speece, 1975b).

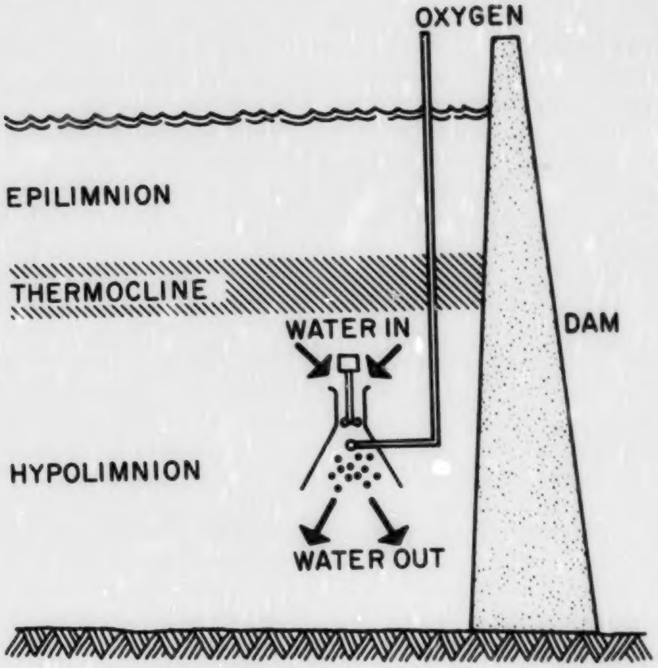

OXYGEN
EPILIMNION
THERMOCLINE
WATER IN
DAM
HYPOLIMNION
WATER OUT

Figure B-17. Downflow bubble contact aerator in position for proposed hypolimnetic oxygenation (Speece, et al., 1974).

and cause an upwelling. This upwelling may penetrate the thermocline in some cases, and therefore be unacceptable. As far as we know, the DBCA has not been used for full scale oxygenation of a lake's hypolimnion.

Whipple (1975) has designed and tested another oxygen injection system (Figure B-18). His system is constructed of wood and is suspended just above the lake's bottom by a raft. He tested it at Spruce Run Reservoir, Clinton, New Jersey, during 1973-74. It has many features in common with the partial air lift designs (Figures B-2 and B-3) since hypolimnetic water is circulated by the "air lift" principle and the water is not upwelled to the surface. According to Whipple, the aerator did not function as well as he had expected. This may have been due in part to the equipment design, and in part to the experimental design. The experimental design involved an attempt to oxygenate only one hypolimnetic arm of the reservoir. Experience elsewhere indicates that this may not be possible since the water currents generated by the oxygenation equipment will tend to distribute the oxygenated water throughout the hypolimnion.

Seppänen (1974) described the design and operation of Isteri's aerator in lakes Hemtrask and Kiteenjarni, Finland (Figure B-19). This device was used to oxygenate lake waters during ice cover. Seppanen intended to use the aerator for hypolimnetic oxygenation as well. It is similar in concept to downflow air injector systems previously discussed. Water is withdrawn from the hypolimnion and discharged to the hypolimnion at high velocities by a mechanical water pump. Oxygen is injected above the pump and the water forces the bubbles into the hypolimnion. Seppänen reported a problem with a gas pocket forming at the top of the tube's arch. This may have been due to bubble coalescence within the downflow tube and the upwelling of these large bubbles within the tube.

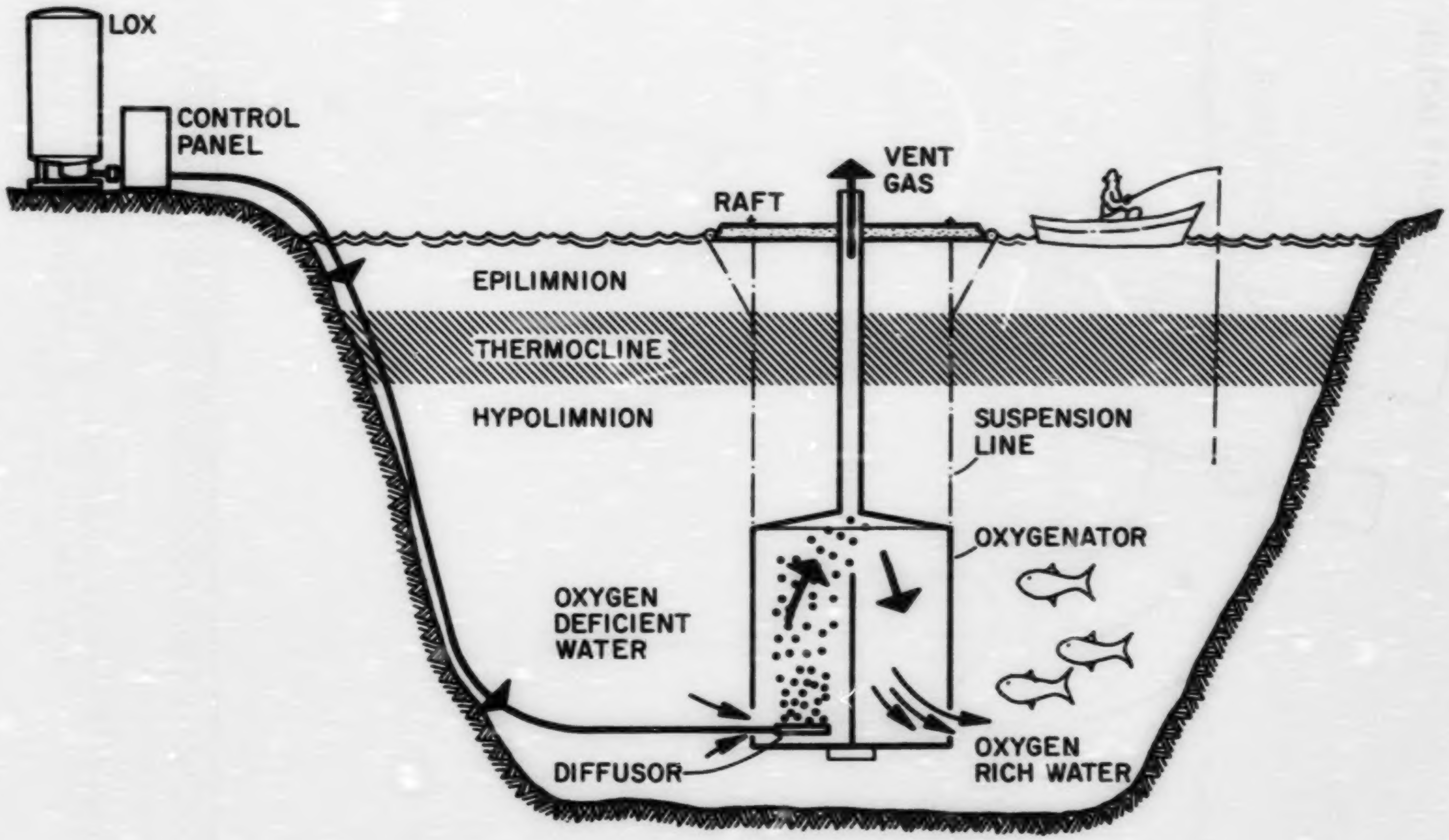

LOX
CONTROL PANEL
VENT GAS
RAFT
EPILIMNION
THERMOCLINE
HYPOLIMNION
SUSPENSION LINE
OXYGENATOR
OXYGEN DEFICIENT WATER
DIFFUSOR
OXYGEN RICH WATER

Figure B-18. Hypolimnetic oxygenation system used at Spruce Run Reservoir, New Jersey (Whipple, 1975).

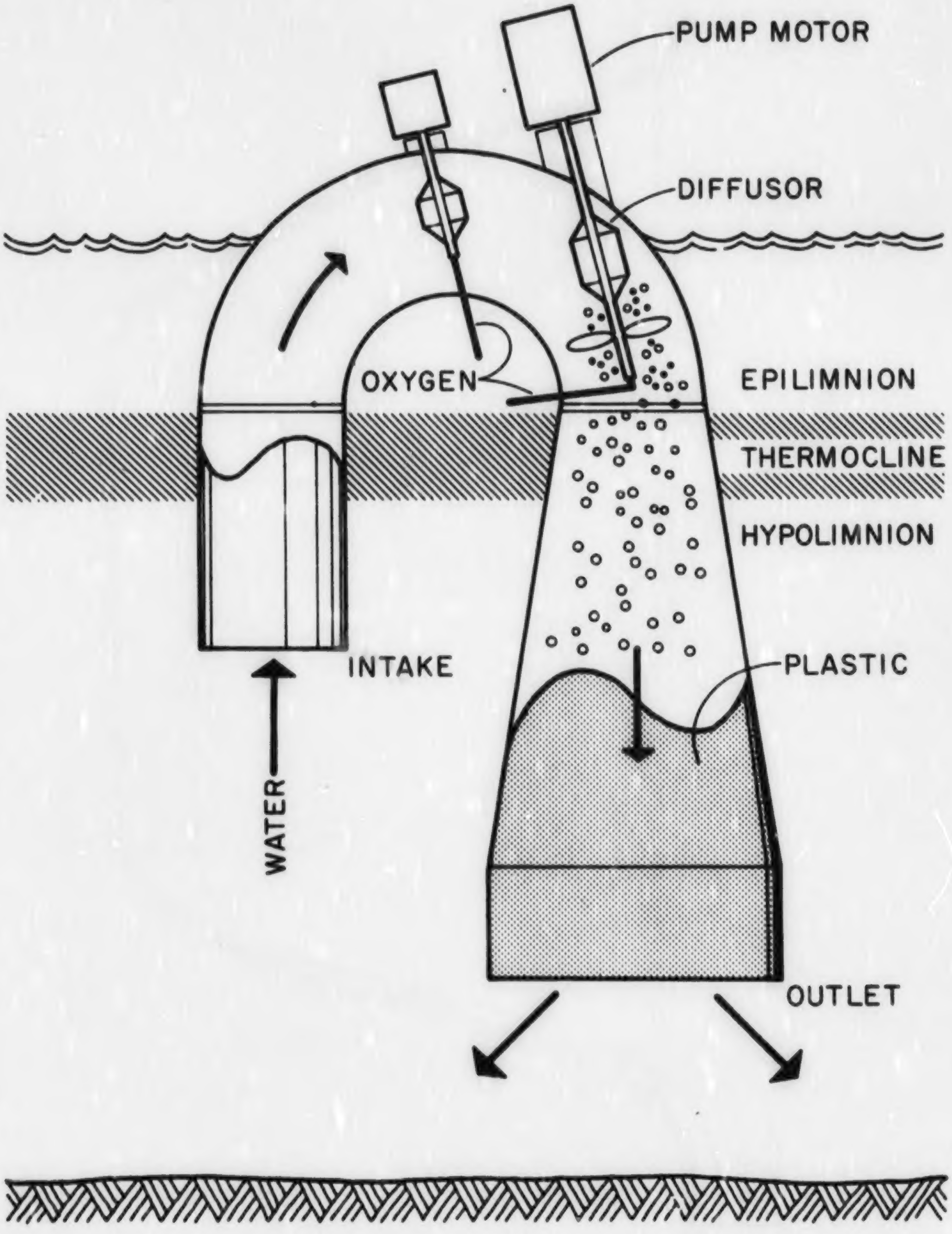

PUMP MOTOR
DIFFUSOR
OXYGEN
EPILIMNION
THERMOCLINE
HYPOLIMNION
INTAKE
PLASTIC
WATER
OUTLET

Figure B-19. Isteri oxygen injection system used to oxygenate under the ice in Lakes Hemtrask and Kiteenjarni, Finland (Seppänen, 1974).

SECTION VIII

APPENDIX C

AIR SUPPLY LINE AND COMPRESSOR SELECTION

Following determination of total air requirements and diffuser design (discussed in Chapters II and III), it is necessary to design the supply line and select an appropriate compressor.

Design Parameters

Air pressure requirements depend on depth of water at which the air is released, length and diameter of the air line between the compressor and the point of injection, type of diffuser used and type of filter used to remove oil from the air. Of these conditions, the depth of air injection is usually the most important. It is highly desirable to inject the air as deep as possible to maximize the water flow and assure oxygen saturation at the surface.

The pressure required to deliver air from the compressor to the diffuser depends on the depth of release and losses in the supply system. The system should be designed to provide from 5 to 10 psi at the diffuser. The number of diffusers or hole spacing can be adjusted to provide the required air flow rate and a uniform distribution of bubbles.

Head losses in the air supply line are a function of pipe material and diameter, flow rate and operating pressures. The pressure loss is directly proportional to the square of the flow rate and inversely proportional to the fifth power of the pipe diameter. Nomographs for computation of pressure changes in compressible flow lines are available in "Flow of Fluids through Valves, Fittings and Pipes, Technical Paper 410, CRANE CO., 4100 S. Kedzie Avenue, Chicago, Illinois, 60632. As an example, for air flowing through a 2 inch nominal diameter schedule 40 steel pipe at 100 psi and 60°F the pressure drop (h_ℓ) per 100 feet as a function of air flow is shown below:

Free Air Flow (SCFM)	h_ℓ/100 ft (psi)
50	.019
100	.070
200	.264
300	.573
400	1.00

Free Air Flow (SCFM)	h_ℓ/100 ft (psi)
500	1.55
600	2.21
700	3.00
800	3.90
900	4.91
1000	6.06

The gauge pressure required at the compressor discharge (following any filter) is given by:

$$P_{required} = \Delta P + h_\ell + \text{Depth}\ (\frac{14.7}{33}) \qquad \text{(C-1)}$$

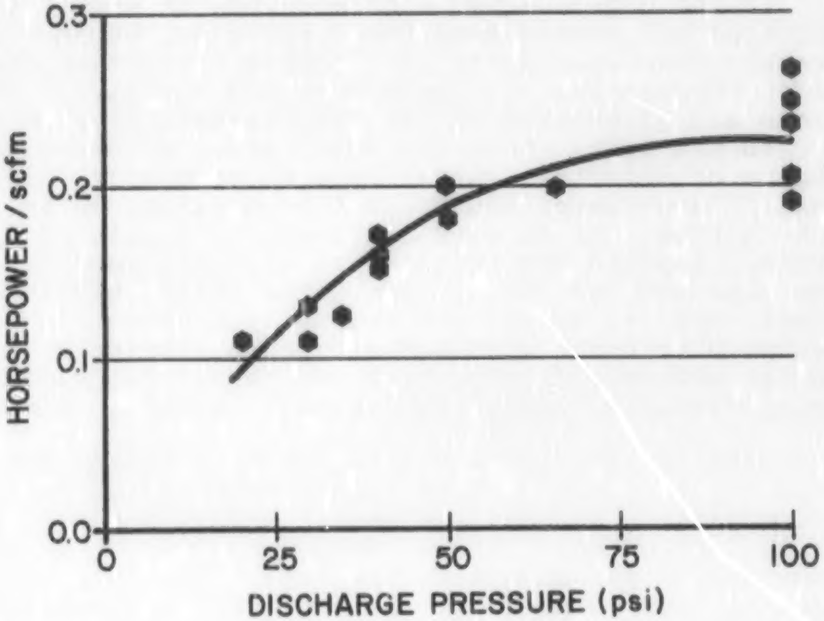
where: ΔP = pressure drop across orifice

h_ℓ = pressure drop in supply system

The pressure required should be computed for a number of pipe sizes so that alternative compressor costs can be compared to pipe costs.

It is important not to use a compressor which far exceeds the pressure required to inject the air. Too often a double stage air compressor with a working pressure in excess of 100 psi is used to inject air at a 50 foot depth (22 psi) or less. This wastes energy and greatly increases operating costs. For depths less than 50 feet a single stage reciprocating air compressor is usually most satisfactory (working pressure of 50 psi or less). Depths greater than 75 feet usually require a double stage reciprocating air compressor. The discharge pressure should be selected to produce maximum efficiency.

Figure C-1 shows the approximate horsepower required per standard cubic foot per minute of air delivered at various pressures. These data were extracted from Atlas Copco brochure 5SC1-1273 for a variety of compressors. It should be noted that reciprocating compressors are more amenable to adjustment of pressure and flow rate than are rotary type compressors. For example, the Atlas Copco BE23-1160 can be adjusted to operate at from 20 to 50 psi with free air flow rates ranging from 101 to 119 SCFM. The horsepower required per SCFM of air at the different pressures is shown in Figure C-1. For pressures less than 20 psi, commercial air blowers may be more efficient.



Selection and Installation

Air Line --

The sizing, choice of materials, methods of assembly and installation are all important considerations. They all affect capital costs, operating costs and problems such as line breaks. The proper design, construction and installation of the air line extending from the air compressor into the lake will greatly reduce future problems and increase operating efficiencies. Some of the considerations are discussed below.

Small diameter, light weight lines should be avoided on lakes with recreational boating. Some of these lines can be hooked by boat anchors, pulled to the surface, dislocated and even broken. A variety of pipe line materials may be used, such as steel, polyethylene and PVC plastic. Each material has its advantages and disadvantages.

Generally, it is advisable to use galvanized steel pipe from the compressor to the water. Unless this section is buried or covered, it will be most exposed to vandalism and liability problems. If the compressor does not have an aftercooler for the compressed air, then this section of pipeline must be heat resistant. Discharge temperatures can exceed 200°F and will melt some plastics.

If the pipeline is on an incline, it should be adequately anchored and braced near the compressor, but not on the compressor discharge port. A flexible connection should be provided between the discharge port and the pipe. Steel air lines are often used in the lake as well as from the compressor to the lake. However, steel pipe is generally not the best choice of material. Steel pipe is expensive, difficult to install underwater and subject to breakage on an irregular lake bottom. It is very difficult to repair if a break does occur. Repairs may require the use of divers or lifting the pipe back to the surface. The inflexibility of the steel, and its weight are primarily responsible for its tendency to break either during installation or after it is on the bottom. This problem can be partially overcome by using flexible joints between each length of pipe.

Plastic pipe is generally the best choice for underwater use. It is cheaper, lighter and much easier to install. PVC plastic pipe has been widely used. It comes in lengths of 20 feet or more, which can be glued together at the site. However, it is subject to breakage. Flexible, polyethylene plastic pipe is probably the best choice for most underwater air lines since it comes in much longer lengths. It can be purchased on large diameter spools. The polyethylene pipe is more rigid when cold, and it may be necessary to discharge heated air (e.g. from a compressor) or hot water through the pipe in order to unwind it from the spool.

The installation procedures will depend on a variety of factors including the pipe material, diameter, weight and whether it will be suspended at the lake's surface or submerged and anchored at the bottom. If the lake is closed to the public, at least in the area used by the aeration system, it may be possible to simply suspend the air line by floats at the surface, extending from the shore to the injection location. This may block some boat traffic, but it is the easiest and cheapest installation. The pipe is accessible for repairs or modifications, and it can be easily removed. However, in many cases this arrangement is undesirable or impossible and the line must be submerged.

If a light weight, flexible plastic pipe is used the first step in installation is to assemble or unwind it from a spool, and stretch it out on the surface of the lake from the shoreline to past the point of air injection. This profile can be measured by stretching a rope from the shore at the lake's surface to a float in the lake. Soundings can be made along the rope with a weighted line, or recording sonar.

After the air line is stretched out on the lake's surface and securely attached at the shoreline, weights or anchors can be added to sink it to the bottom. The weights should be added starting at the shore and working into deeper water. If the end of the air line is attached to a hypolimnetic aerator or some other device, then it is desirable to use a flexible connection. A flexible rubber pressure hose works well. This will allow for some shifting of the device without putting excessive stress on the connection.

Compressor --

After determination of required air flow rates and pressures, it is recommended that a number of compressor manufacturers be contacted to obtain detailed information on price and performance characteristics.

SECTION IX

APPENDIX D

HYPOLIMNION AERATOR SIZING

The following analysis provides a simplified method to estimate air requirements and pipe diameters for simple hypolimnion aerators. The analysis is based on the assumption that the theoretical head available results from the difference in density between the air-water mixture in the pipe and the outside water. It is further assumed that one-half the theoretical head would be used to pump water up to the surface and an equal amount would be used to pump the aerated water back down to the hypolimnion.

Figure D-1 is a definition sketch of the system. The theoretical lift, ΔH is obtained by solving the equation:

$$\Gamma_m (L + \Delta H) = \Gamma_w L \qquad \text{(D-1)}$$

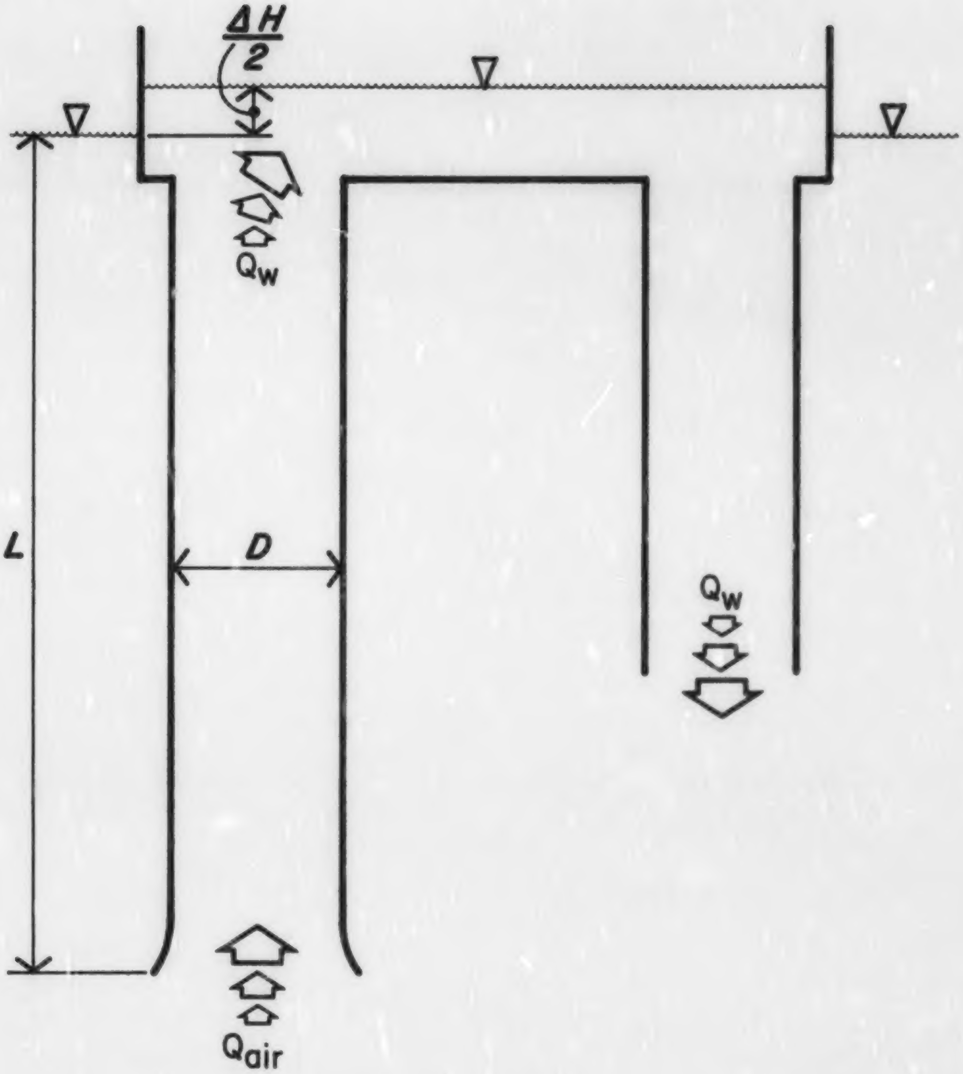
where: Γ_m = density of air-water mixture
L = depth of air release
Γ_w = density of water

$$\Delta H = \frac{\Gamma_w L}{\Gamma_m} - L$$

The average density of the air-water mixture is given by:

$$\Gamma_m = \frac{Q_w \Gamma_w + Q_a \Gamma_a}{Q_w + \overline{Q}_a} \qquad \text{(D-2)}$$

where: Q_w = water flow rate
Q_a = volumetric air flow rate
$\overline{Q}_a$ = mean volumetric air flow rate



$\frac{\Delta H}{2}$
Q_w
L
D
Q_w
Q_{air}

Figure D-1. Definition sketch for air induced flow.

$$\Delta H = \frac{\Gamma_w(Q_w + \overline{Q}_a)}{Q_w \Gamma_w + Q_a \Gamma_a} L - L \qquad \text{(D-3)}$$

for small ratios of air flow rates compared to water flow rates

$$\Delta H = \frac{\Gamma_w(Q_w + \overline{Q}_a\ )}{Q_w \Gamma_w} L - L = \frac{Q_w + \overline{Q}_a}{Q_w} L - L \qquad \text{(D-4)}$$

The mean volumetric air flow rate, $\overline{Q}_a$ can be shown to equal:

$$= \frac{Q_a\ 34 \ln \left(\frac{L + 34}{34}\right)}{L} \qquad \text{(D-5)}$$

where Q_a = free air delivery, in SCFM.

therefore:

$$\Delta H = \frac{34\ Q_a \ln \left(\frac{L + 34}{34}\right)}{Q_w} \qquad \text{(D-6)}$$

Neglecting the effect of the air bubbles interspersed with the water (probably valid for low air:water ratios) there are three major head loss terms.

1. exit loss, h_L^1

$$h_L^1 = \frac{v^2}{2g} = \left(\frac{Q_w}{A}\right)^2 \times \frac{1}{2g} = \frac{Q_w^2}{\left(\frac{\pi D^2}{4}\right)^2 \times 2g} = \frac{8Q_w^2}{\pi^2 D^4 g} \qquad \text{(D-7)}$$

where: v = velocity (fps)
g = acceleration of gravity (ft./sec^2)
A = cross-sectional area of pipe (ft^2)
D = pipe diameter (ft)

2. friction loss, h_L^2

$$h_L^2 = \frac{fL}{D} \times \frac{v^2}{2g} = \frac{fL}{D} \times \frac{8Q_w^2}{\pi^2 D^4 g} = \frac{8fLQ_w^2}{\pi^2 D^5 g} \qquad \text{(D-8)}$$

3. entrance loss, h_L^3

$$h_L^3 = K_L \times \frac{v^2}{2g} = \frac{K_L \times 8Q_w^2}{\pi^2 D^4 g} \qquad \text{(D-9)}$$

where: K_L = entrance constant

From our initial assumption:

$\Delta H = 2 \times (h_L^1 + h_L^2 + h_L^3)$ or

$$\frac{34Q_a \ln\left(\frac{L + 34}{34}\right)}{Q_w} = \frac{2 \times 8Q_w^2}{{}^2D^4 g} \times \left(1 + \frac{fL}{D} + K_L\right) \qquad \text{(D-10)}$$

rearranging to isolate Q_w and Q_a:

$$\frac{Q_w^3}{Q_a} = \frac{34 \ln\left(\frac{L + 34}{34}\right) \; {}^2D^4 g}{16\left(1 + \frac{fL}{D} + K_L\right)} = \frac{673\, D^4 \ln\left(\frac{L + 34}{34}\right)}{1 + \frac{fL}{D} + K_L} \qquad \text{(D-11)}$$

This relationship was used to prepare Figure D-2 which shows the ratio Q_w^3/Q_a for various pipe diameters and lengths. A friction factor f, of 0.02 and K_L value equal to 0.5 were assumed for this plot.

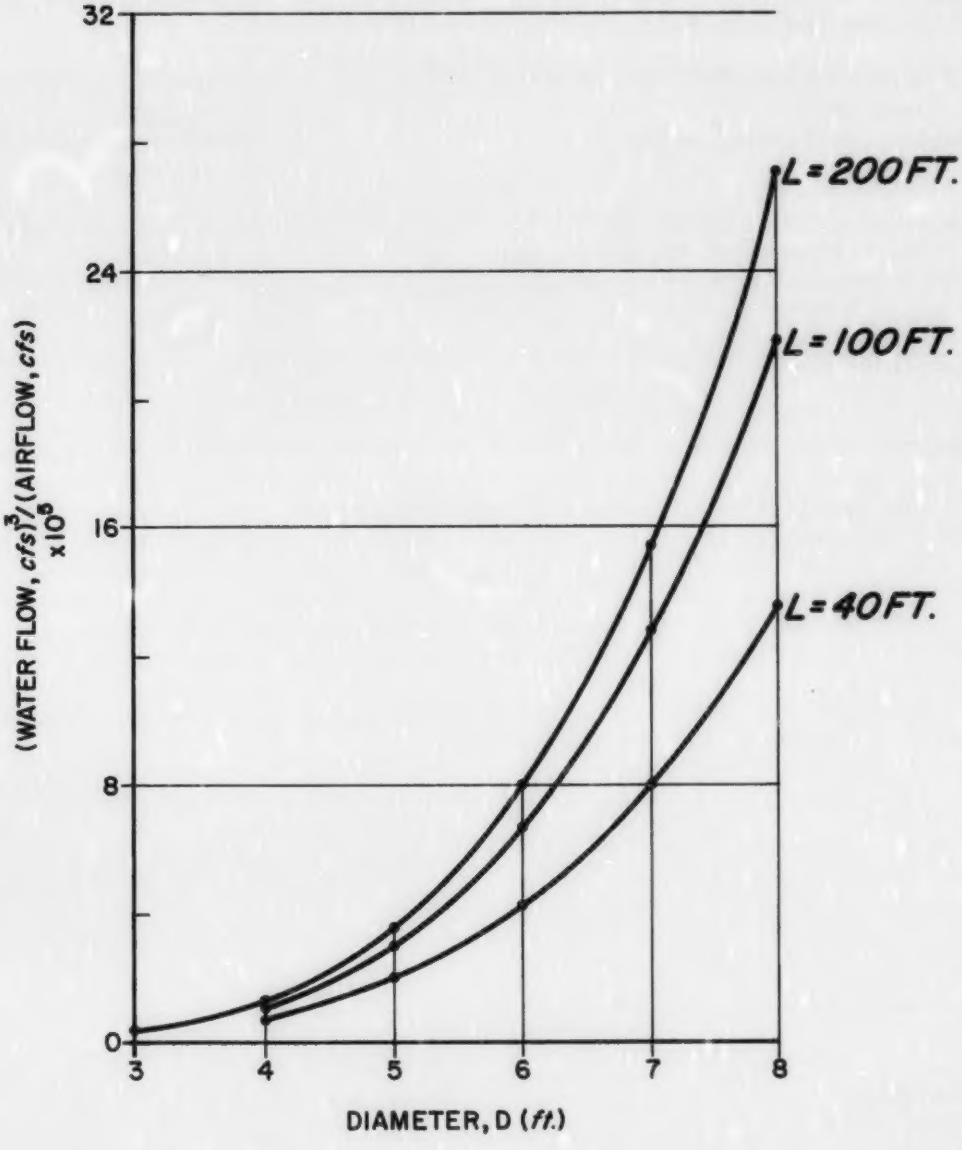


Figure D-2. Ratio of water flow to air release for different pipe diameters and depth of release.